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SYSTEMATIC EQUIPMENT PERFORMANCE ANALYSIS OF A KRAFT PROCESS THROUGH NEW AND ADAPTED KEY PERFORMANCE INDICATORS

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DEDICATION

To my parents, Abdelhak and Souad, for their endless and unconditional love and support.

To my grandmother, mama Bariza, with love. You may be gone, but you will never be forgotten.

Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.

-Winston Churchill-

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RESUME

L’industrie des pâtes et papiers occupe une place importante dans l’économie du Canada et est un acteur clé quant à la croissance de son produit intérieur brut [1]. De plus, l’industrie papetière crée plus de 320 000 emplois directs et indirects pour les Canadiens [1]. Toutefois, cette industrie est l'une des plus grandes consommatrices d'énergie, consommant environ 30 % de l'énergie totale utilisée par les industries manufacturières canadiennes [2]. Cependant, au cours des deux dernières décennies, l'industrie des pâtes et papiers a été confrontée à une crise sans précédent en raison de la concurrence des économies émergentes comme l'Inde et la Chine, des règlementations environnementales strictes et contraignantes et des prix élevés des énergies. Parce que l'énergie est une composante importante des coûts de production (environ 25% des couts de production), pour rester compétitives, les papetières se voient donc obligées de réexaminer leur procédé afin de réduire leurs factures énergétiques et leurs consommations d’eau et de produits chimiques et ainsi ne pas perdre leur position concurrentielle. En outre, le secteur a réduit sa consommation d'énergie en moyenne de 1 % par an depuis 1990 [3]. De ce fait, plusieurs techniques d’intégration de procédés existent. Elles se basent sur des approches conceptuelles et graphiques ou encore mathématiques. Ces méthodes d’optimisation et d’intégration de procédé appliquées sur des usines canadiennes ont donné des résultats intéressants. Toutefois, dans la plupart des méthodes actuelles d’optimisation de procédé, il est assumé que les équipements dans l’usine opèrent efficacement. En réalité, ceci n’est pas toujours le cas ; ce qui peut fausser les résultats d’une analyse de performance.

Par conséquent, l'analyse de performance des opérations unitaires du procédé est une étape préliminaire importante avant toute mesure d'intégration. En fait, les équipements ayant une mauvaise performance peuvent augmenter la demande globale du procédé en énergie et en matière et discréditer les résultats des procédures d’intégration.

L'objectif principal de cette thèse est de développer, d'appliquer et ensuite de valider une méthodologie systématique d'analyse de performance des équipements du procédé Kraft, en termes d'énergie, d'eau et d'utilisation de produits chimiques à l’aide de nouveaux indicateurs de performance.

La méthodologie s’articule autour de quatre étapes successives à travers desquelles les opérations unitaires sont examinées pour évaluer comment leurs besoins énergétiques, d'eau et des produits chimiques peuvent être réduits en augmentant leurs propres performances. La méthodologie comprend: (i) le développement et le calcul des indicateurs de performance clés pour chaque unité opératoire, (ii) l'identification des écarts importants par rapport au rendement cible et donc la localisation d'un mauvais fonctionnement et, (iii) le diagnostique des causes d’inefficacité et des recommandations de mesures correctives.

Les techniques existantes pour évaluer la performance des équipements considèrent l’utilisation efficace d'énergie et d'eau. La présente étude considère l’utilisation de l'eau, l'énergie et les produits chimiques au sein du procédé. En outre, il prend en compte les interactions entre les opérations unitaires et plus d’un indicateur clé est utilisé pour évaluer la performance des équipements. Une étude de ce type n’a jamais été effectuée sur une usine Kraft Canadienne. Ce qui rend cette étude originale tant d’un point de vue méthodologie que résultats obtenus.

Dans un premier temps, la réconciliation de données et la détection des erreurs grossières sont effectués pour produire un modèle fiable du procédé étudié pour ainsi obtenir des résultats cohérents et sûrs lors d’une analyse de performance. La réconciliation des données et la détection des erreurs grossières ont également été utilisées pour localiser et identifier les opérations unitaires présentant des inefficacités. La réconciliation et la détection des erreurs grossières sont considérés dans cette étude comme premiers indicateurs de performance. Une analyse de l'efficacité exégétique a été effectuée afin d’identifier les opérations unitaires thermodynamiquement inefficaces. L’efficacité exégétique est l’indicateur clé pour l'utilisation de l'énergie. Une fois ces deux analyses effectuées, les opérations unitaires soupçonnées d'avoir de mauvaises performances sont identifiées. Ces opérations unitaires sont ensuite analysées avec un ou plusieurs indicateurs de performance qui leur sont spécifiques, développés suite à une analyse adimensionnelle autour des unités opératoires clés, et enfin des projets d'amélioration sont proposés suite aux diagnostics établis.

Enfin, l'intérêt de cette méthodologie est démontré dans le cas d'une usine de pâte kraft située dans l'Est du Canada. L'usine produit une moyenne de 280 adt / j de pâte à partir de laquelle du papier journal est fabriqué. La méthodologie a été démontrée pour être en mesure d'améliorer l'efficacité globale du procédé en termes d'utilisation d'énergie, d'eau et des produits chimiques.

ABSTRACT

The Canadian pulp and paper sector is an important key player in the country's economic growth and gross domestic product [1], providing over 320, 000 direct and indirect employment opportunities for Canadians [4].

Pulp and paper industry in Canada is one of the largest energy-consumer amongst all industries in Canada, consuming approximately 30% of the industrial energy [2]. However, during the last two decades, the pulp and paper sector has been facing an unprecedented crisis due to competition from emerging economies like India and China, stringent environmental regulations and high energy prices. Because energy is a significant production-cost component (about 25% of the total production cost), in order to remain competitive, the sector has made efforts towards identifying ways to improve the energy efficiency through implementing energy recovery systems. The sector has also reduced its energy use by an average of 1% annually since 1990 [3]. Despite these improvements, the pulp and paper industry still seeks ways to identify inefficiencies and improve its overall energy and water utilization. Many process integration (PI) techniques have been developed and gave encouraging results. These techniques use both conceptual and mathematical approaches. However, these techniques consider that the unit operations in place function efficiently, which is often not the case in real operating pulp mills. Therefore, analysing the performance of unit operations is an important step prior to any process integration technique. In fact, equipment with poor performance could increase the energy and water demand of the overall process and discredit the results of energy and utility enhancement procedures.

The objective of this thesis is to develop, apply and validate a methodology for Kraft process equipment performance analysis in terms of energy, water and chemical utilization by means of new and adapted key performance indicators.

The core of the methodology consists in four successive stages through which the unit operations are examined to evaluate how their energy, water and chemical requirements can be reduced by increasing their own performance. The steps comprise: (i) the computation of key performance indicators for each piece of equipment, (ii) the identification of significant deviations from the

target performance, and therefore the location of poor performance unit operation and, (iii) diagnosis of the causes of inefficiencies and the proposal of remedial actions.

The existing techniques for the evaluation of equipment performance include either energy or water utilization efficiency. The current study considers water, energy and chemical utilization in the process. It also takes into account the interactions between unit operations and uses more than one KPI to evaluate the performance of the process operations.

At first, data reconciliation and gross error detection are performed to produce a reliable model of the process studied and obtain reliable results when performing performance evaluation. Initially, data reconciliation and gross error detection are used to locate and identify process leaks and biases. A strong measurement adjustment is considered in this study as a first key performance indicator (KPI). An exergy efficiency analysis is performed to identify poor energy efficiency unit operations. Exergy efficiency is the KPI for energy utilization. Once these two analyses have been performed, a list of unit operations suspected to have poor performance is constructed. These unit operations are further evaluated by means of KPIs developed based on a dimensional analysis and enhancement measures and improvement projects are proposed according to the diagnoses established.

The interest of this methodology is demonstrated in the case of an operating Kraft pulp located in Eastern Canada. The mill produces an average of 280 adt/d of pulp from which newsprint is made. The methodology has been demonstrated to be able to improve the overall efficiency of the process in terms of energy, water and chemical utilization through an adequate evaluation of its equipment.

This thesis provides mill engineers with a systematic and strategic way to evaluate the performance of their unit operations by means of new KPIs.

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LIST OF SYMBOLS AND ABBREVIATIONS

Adt	Air dried ton
A	Incidence matrix
A_u	Incidence matrix of unmeasured variables
A_x	Incidence matrix of measured variables
BL	Black liquor
C_p	Heat capacity
DR	Data reconciliation
GE	Gross error
GED	Gross error detection
GL	Green Liquor
GLR	Generalized likelihood ratio
g_m	Function of the model constraints
H	Enthalpy
H_0	Null hypothesis, no gross error is present
H_1	Alternate hypothesis, at least one gross error is present
LS	Least squares
m	Number of constraints
n	Number of variables in the system
NLP	Non linear programming
Odt	Oven dried ton
P	Projection matrix (in chapter 3)
P	Pressure (in chapter 4)

Q Matrix of dimension (m x m)

Q_1 Matrix of dimension (m x n)

Q_2 Matrix of dimension (m x m-n)

r Vector of constraints residuals

R_1, R_2 Triangular matrices obtained by QR factorization of the incidence matrix

R Ideal gas constant

s Standard deviation of a sample

T Temperature

u Vector of unmeasured, observable variables

V Matrix of variance of the system

W Matrix of covariance of the system

WBL Weak black liquor

x Vector of true variables

y Vector of measured variables

SUPERSCRIPTS

T Transpose

GREEK

α Confidence level, or significance level, used in statistical hypothesis test

β Modified confidence level for statistical power test

ε Vector of errors

μ Mean value of a sample

σ Standard deviation

γ Test result

χ^2 Chi-squared distribution

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CHAPTER 1: INTRODUCTION

1.1 Context of the study

The economic stability of any developed country depends strongly on the dynamism of its industries. On account of its rich and abundant natural resources, Canada produces and exports fossil fuel energy, forestry and pulp and paper products, among its major outputs. However, these natural resources industries are energy intensive. In 2008, the manufacturing sector accounted for 67% of the total consumption of the country; 14% are directly attributable to the pulp and paper industry [5, 6]. Wood from the forest is an abundant source of renewable biomass provided it is managed responsibly. Indeed, Canada has about 10% of the world's forests with a total of 229 million hectares (ha). Because of this, the turnover in total exports of forest products reaches 68,4 billion dollars, of which 33.5 billion dollars from pulp and paper (P&P), representing 1.2 % of the gross domestic product [1, 3].

However, the Canadian pulp and paper industry has been facing a long lasting crisis for the past twenty years. With the rising costs of energy and chemicals, and with the introduction of new environmental standards, the industry must improve its current process to face this new reality. Several other factors contribute to the worsening of the financial crisis that the industry has been experiencing. The emergence of information technology systems provides a new medium of information, other than paper and thus, decreasing the demand for commodity paper products such as newsprint, the traditional mainstay of the Canadian industry, as well as other printing and writing grades. The gross domestic product from the paper sector has steadily declined since 2007, ranging from $ 5.8 billion in 2007 to $ 3.6 in 2012 [1, 3]. Moreover, major fluctuations in the prices of raw materials have been fundamentally changing the way companies act, react and move up and down the value-chain. This has been the topic of much research interest for the past few years. Simultaneously, new large and modern P&P plants have been built in tropical regions endowed with low labor costs and fast growing forests with 10 to 20 year-maturation periods versus 50 to 75 in Canada. To overcome this crisis, some companies have adopted merger and acquisition strategies. Others have invested capital and effort to reduce their operating costs by reassessing their heat transfer networks. Paradoxically, at the same time, investments in research and development have been significantly reduced (like all other variable costs of the companies). Canadian Pulp and Paper companies must reinvent themselves in the long term by investing in projects centered on technological innovation and improve existing processes by increasing equipment performance and optimizing the use of material and energy.

It is in this uncertain and volatile economic environment that some companies have tried to expand their product portfolios to diversify their sources of income, while consolidating their assets by reducing their operating costs. The Canadian P&P industry has been implementing novel transformative technologies and developing products derived from wood biomass to penetrate new markets. Biosensitive packaging materials for food products, security papers with embedded codes or nanocrystalline cellulose are examples of such products. They are essentially cellulose based, as is paper. The forest biorefinery is also an appropriate solution to help the paper industry face the crisis. The concept of the biorefinery is to exploit the main components of the wood to produce high value-added products. This alternative offers the pulp and paper industry, which has been struggling to operate in this highly unstable environment, a solution to deal with the crisis, and a way to contribute to the development of a bio-economy.

This implementation of alternative papermaking-biorefinery would be possible insofar as the receptor-mother-plant is optimized in terms of energy use, water and chemicals, and certain pieces of equipment are modified or improved. Optimization methods and process integration techniques applied to Canadian plants have produced encouraging results, providing enough energy and material to allow the implementation of a biorefinery [7]. However, it is assumed in most current optimization methods, that the equipment and unit operations in the plant operate effectively. In reality, this is not always the case; and this could make the optimization procedure biased. A new approach that takes into account this scientific gap is necessary.

1.2 Problem

The Canadian paper industry is one of the oldest industries in the country. It emerged in an environment (in the 1930's) where energy and water costs were very low, which is not the current reality. It is therefore essential to improve the performance of the Kraft process and reduce energy, water and chemicals consumption in order to help the integration of biorefinery, face a competitive market and make it more profitable and economically sustainable. Several optimization techniques already exist and have been widely applied. One can cite the pinch analysis applied to energy and water or the mathematical optimization methods, as presented and explained in the literature review. However, these optimization methods have been mostly used with the view that the equipment operates efficiently or as it has been intended, which is often not the case. Equipment performance analysis is an essential step before any measure of improvement that requires major investments.

One way to evaluate the performance of equipment is to use specific key indicators. The use of indicators as a calibration tool is a common practice to measure the variability and correct the operation of a process. Several performance indicators exist but definitions as well as mode of use vary, even though they all have the same goal which is to evaluate the performance of an operation of a process from a particular point of view.

Although some performance indicators already exist, there are still major gaps in their industrial application. Most existing performance indicators are generic (no specific to the Kraft process) and therefore ill-suited to the processes of pulp and paper. In addition, existing performance indicators do not take into account the specificities of the equipment in place, moreover, there are no performance indicators linking the operating conditions of an operation to the intrinsic design of the equipment.

On the other hand, the performance evaluation studies of pulp and paper processes take into account the energy and water variables only, and exclude the chemicals. The chemicals used in the Kraft process have become more expensive over the past decades. Thus, the evaluation of the performance of the unit operations should include the evaluation of the chemical process performance. It is therefore necessary to develop new performance indicators that take into account the specific design of the equipment, the operating conditions, and the relevant parameters to control or optimize energy, water and raw material usage by the Kraft process during its operations. These indicators will not only facilitate the assessment of the performance but also the diagnosis of the inefficiencies.

The synthesis of the knowledge gaps leads to the necessity to develop a systematic approach that will contribute to reach the following objectives:

- Build a simulation based on a congruent set of data that represent the steady-state of the process (data reconciliation);
- Systematically identify equipment and unit operations that have poor performances with respect to energy, water, and raw materials utilization;

- Diagnose effectively the causes of inefficiencies, and;
- Propose improvement projects to address inefficiencies.

The work carried out within the framework of this thesis addresses these issues by developing a systematic methodology for equipment performance analysis.

1.3 General objective

The main objective of this work is to develop new key performance indicators, specially tailored for the Kraft process, and to quantify the performance of individual equipment for the use of energy, water and products, in order to improve the performance of the overall process.

1.4 Structure and organisation

This thesis consists of eight chapters and is supported by four papers submitted for publication. A brief introduction was presented in Chapter 1. Chapter 2 is devoted to the review of the literature followed by a description of the methodology. Chapters 3, 4, 5 and 6 are submitted papers on data reconciliation, exergy analysis, development of new key performance indicators based on dimensional analysis, and the results of the equipment performance analysis, respectively. A general discussion about the thesis is presented in Chapter 7, followed by a concluding Chapter. Scientific contributions and recommendations for future work are clearly stated in the individual papers.

CHAPTER 2: LITERATURE REVIEW

The background and literature review is divided into three parts; the first one presents the description of the Kraft process specifications followed by the process integration techniques and the optimization methods. The second part is devoted to the dimensional analysis, the equipment performance analysis, the data reconciliation, the gross error detection techniques and the exergy efficiency analysis. The final part is a summary and synthesis of the literature review, the identification of the scientific gaps and the presentation of the methodology to fulfill the main objective of the thesis.

2.1 Description of the Kraft process

2.1.1 Importance of paper

Paper is a product of daily consumption, called a commodity product [8]. A trip to a grocery store provides a glimpse of the industry's influence on our daily life [9]. Paper is used for packaging, marketing personal care tissues, and so on. It supports most of our communications. It provides means for the identification of documents, of banking transactions, of the dissemination of information, etc. It is closely tied to activities of humankind. Although paper consumption has declined since the emergence of electronic information and web technologies that have supplanted it [10], the paper remains a necessity of daily life. The uses and applications of paper products are limitless. Also, new specialty products such as biosensitive or smart packaging papers are in constant development.

2.1.2 Pulping and paper making processes

Pulping is the process by which the wood or any other cellulosic raw fibrous material is reduced into fibers. In other words, the lignin which binds the fibers together is dissolved or broken (depending on the process), leaving the cellulose and hemicelluloses free and in fibrous form. This can be accomplished by various methods: mechanical, chemical or, semi-chemical. The latter is a hybrid between the two other methods. Chemical processes are the most commonly used pulping method. They represent 70% of the North American production, 90% of it being attributed to Kraft or the so-called sulphate process [10].

The mechanical pulping consists in mechanically forcing the logs against a revolving stone/wheel (stone ground wood, SGW) which grinds the wood into pulp, under the effect of pressure and heat, by buffing or mechanical friction. The surface of the abrasive stone is washed to recover the liberated fibers and prevent its damage.

The chemical pulping, as opposed to the mechanical pulping, consists in cooking wood chips with appropriate chemicals in an aqueous solution at elevated pressure and temperature. The objective is to chemically dissolve the maximum of lignin while leaving the cellulose and hemicelluloses in the form of intact fibres. The two main chemical methods are the Kraft process (alkaline) and the sulfite process (acid) [10].

2.1.3 The Kraft process

The Kraft process is known to be energy intensive and a large consumer of chemicals. The main purpose of a Kraft pulp mill is to produce pulp at a given Kappa number[1] or brightness while minimizing energy costs, utilities and chemicals used [11]. The Kappa number describes directly the amount of lignin dissolved. The Kraft pulping entails treatment of woodchips with a mixture of sodium hydroxide ($NaOH$) and sodium hydro-sulfide ($NaSH$). The process can be divided into 2 main lines, the fiber line and the chemical recovery line. Figure 2-1 depicts a simplified flowsheet of the Kraft process. The Kraft process is characterized by its chemical recovery loop, which makes it economically viable and independent in terms of energy and chemicals, if the mill is well managed.

[1] Kappa number is an indication of the residual lignin content or bleachability of wood pulp by a standardised analysis method.

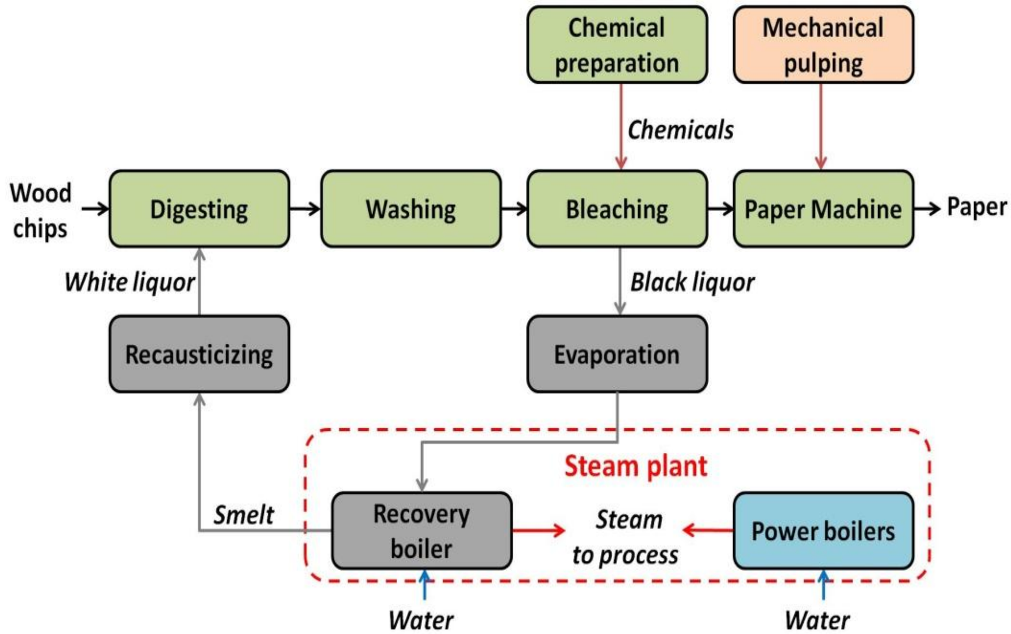

Figure 2-1 : Simplified diagram of the case study Kraft pulp mill

The main purpose of the pulp line is to remove the lignin from the fibers and produce a pulp of good properties of brightness and strength. The lignin is removed in 3 main departments: digesting, washing and bleaching. The lignin removal is accomplished with such chemicals as sodium hydroxide (NaOH) and sodium hydro-sulfide (NaSH) in digesting, and oxygen (O_2) and chlorine dioxide (ClO_2) in bleaching. The two ‘’driving forces’’ for Kraft pulping reactions in the digester are the alkali concentration (as measured either by effective alkali or active alkali) and the temperature [11].

The fiber line starts with the wood reception. The wood is mechanically debarked and chipped; then, the chips are screened to eliminate the fine and over-sized pieces. The removed bark is combusted in the bark boiler and the wood chips retained are sent to the digester after being impregnated by injection of superheated steam. The wood chips are introduced in the cooking vessel along with the white liquor the solution of sodium hydroxide and sodium hydrosulfide and heated up to 170 ° C for about 1 to 2 hours to complete the delignification reactions [8]. The digester is one of the most important unit operations of the Kraft process. It is where the cellulosic fibers are separated from the lignin to form the pulp. After the digesting, the pulp is sent to the brown stock washing section. The washing is performed through a series of counter-current brown stock washers using displacement washing to remove the residual lignin from the fibres. The dissolved lignin and chemicals removed are sent to chemical recovery or back to the digester as dilution water. Figure 2-2 shows a simplified schematic of the washing section.

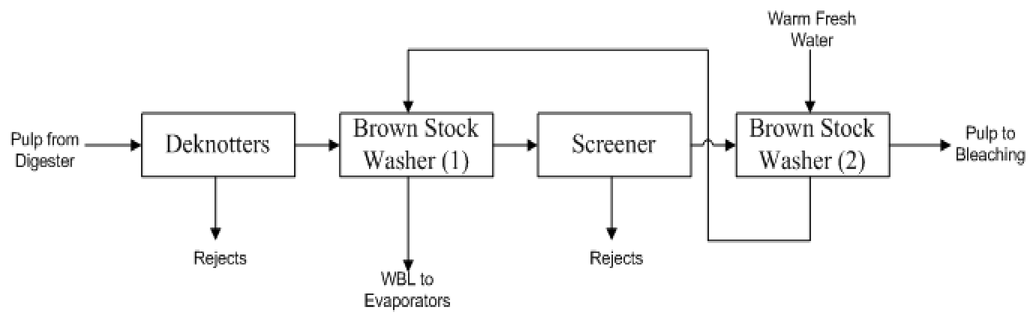

Figure 2-2 : Simplified schematic of the washing department

The washed pulp is sent to the bleaching section where a series of bleaching steps take place using specific reducing or oxidizing bleaching agents. The objectives of bleaching are to remove the residual lignin, to maintain cellulose chain length and to brighten the fibers through different bleaching stages at different pH and temperature conditions and using different bleaching chemicals. A bleaching stage is composed of a bleaching tower, a storage tower and a washer. The simplified bleaching sequence for the case-study mill is depicted in figure 2-3. The bleaching towers are described using the standard name convention for bleaching sequences, more specifically, bleach towers are referenced using letters and subscripts, where the first capital letter refers to the oxidizing/reducing chemical used in the tower and subscripts are used when there is more than one tower using the same bleaching chemical to identify such towers in increasing order. Therefore, as showed in figure 2-3, the bleaching sequence for the studied mill is: D_0EopD_1.

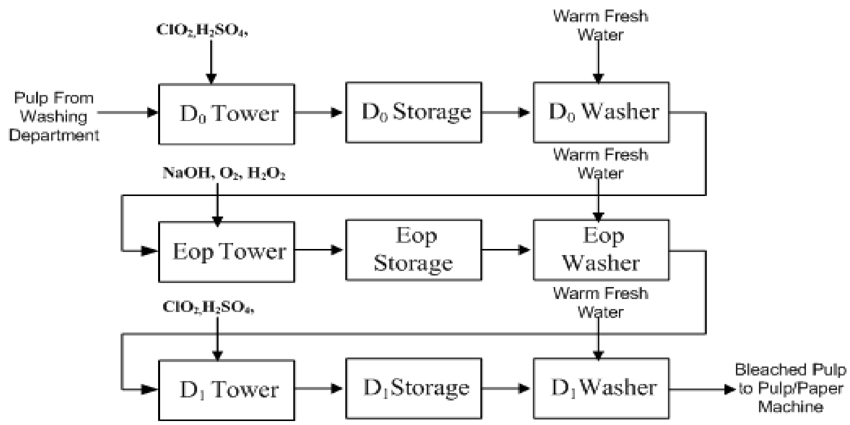

Figure 2-3 : Simplified schematic of the bleaching sequences: D_0EopD_1

The bleached pulp is sent to the pulp or paper machine to finally produce dried pulp or paper to be sold. At this department, the pulp undergoes a final cleaning and screening to remove oversized and bad quality fibers. The filtrate containing fibers is recycled to the bleaching department. Low pressure (LP) steam is injected in the paper machine and in the dryer. This department is generally highly energy intensive. Up to 40% of the total steam consumption is attributable to this department. Figure 2-4 presents a simplified schematic of the unit operations in the paper machine department.

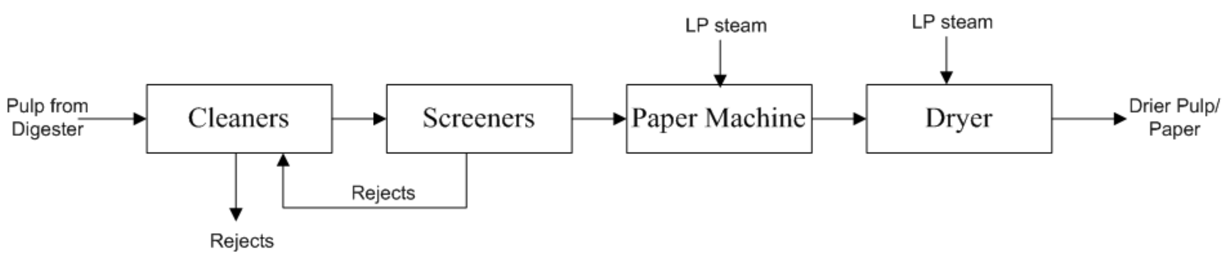

Figure 2-4 : Simplified schematic of the paper or pulp machine department

The chemical recovery line consists in regenerating the chemical agents used in the cooking vessel, and producing steam to supply for the energy demand of the mill. It is necessary to have a recovery loop to make the pulping process economically feasible.

The cooking liquor coming from the digester is sent to the evaporator department. The lignin dissolved in the weak black liquor (WBL) is concentrated (from 15% to more than 60% of dissolved solids) in the multi-effect evaporators and then burnt in the recovery boiler to produce the steam required for the process and to recover the spent chemicals as a smelt, which is sent to the recausticizing department where it encounters a series of reactions to regenerate the white liquor which closes the liquor loop. Impurities introduced from the recovery boiler and from the lime kiln are also removed in this department. Non Process Elements (NPEs)[2] are also removed at this stage; otherwise the overall efficiency of the mill would be compromised. The calcium carbonate is burnt in the lime kiln to regenerate the lime. Some make-up chemicals are sometimes added to the system to maintain the same white liquor quality and therefore the same brightness and quality of the pulp produced. Natural gas is used as a fuel in the lime kiln and also in the power boilers. Figure 2-5 shows the simplified schematic of the chemical recovery department.

[2] Non process elements are introduced into the Kraft pulp mainly through the wood chips. The elements of concern are primarily those that do not form insoluble inorganic compounds in alkaline solutions, i.e. AI, Si, Cl and K, and also transition elements, i.e. Mn, Cu and Fe, and the alkaline earth metals Ca and Ba.

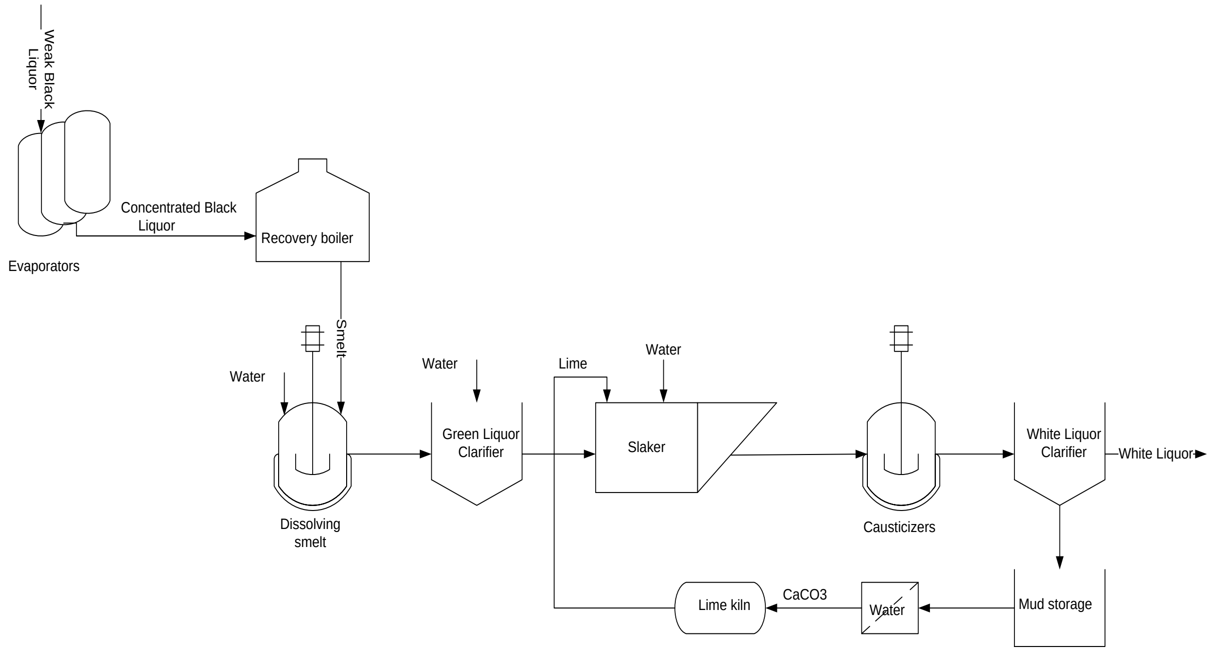

Figure 2-5 : Simplified schematic of the chemical recovery line

To meet the mills energy demand in cold winter conditions, power boilers fired with natural gas are used to supplement the recovery boiler. The number of power boilers in use depends on the production capacity of the mill, the efficiency of its unit operations and the design of the heat transfer network.

Three main reactions take place in the recausticizing department. First, the causticizing reaction that occurs in two steps: the lime reacts first with water ("slaking") to form calcium hydroxide $Ca(OH)_2$, which in turn reacts with sodium hydroxide:

- $CaO + H2O \rightarrow Ca(OH)_2$ (exothermic reaction)
- $Ca(OH)_2 + Na_2CO_3 \leftrightarrow CaCO_3 + 2NaOH$ (equilibrium reaction)

Then, the calcium carbonate is converted to lime in the lime kiln:

- $CaCO_3 + Heat \rightarrow CaO + CO_2$ (combustion of the lime mud)

The bleaching and recausticizing departments are the largest consumers of chemicals and are significant contributors to environmental pollution problems (the sulphide in the white liquor is a contributing factor to the environmental problems) [11]. Several patents have been developed and offer significant improvements over the original process. Blackwell [12] proposes a new design for the recausticizing department, which involves a recirculation of causticizing reaction products to prolong the contact time between the reactants, in order to increase the yield of the reaction.

The bleaching department uses significant quantity of chemicals, and thus generates a large amount of effluents to be treated, and therefore, is a factor of environmental deterioration. Paleos [13] proposes a new method for the treatment of bleaching effluents by discoloration through a macroreticular-resins bed. The effluents lose their organic pigments adsorbed on the resins, and can be discharged, reducing environmental pollution.

Moy and Styan [14] proposed a method for sodium chloride recovery in the chemical recovery loop to reduce the non process elements load and accumulation through an acidification process, precipitation and filtration. Singh [15] proposed a new bleaching process which reduces the amount of water and chemicals used, as well as the quantity of effluents generated. In this method the effluents from the final bleaching step in the chemical recovery department are recycled. Kooi [16] patented a design which does not use any sulfide nor chlorine in the bleaching department, thus reducing the consumption of chemicals and the production of effluents.

2.1.4 Utilities consumption

The Department of Natural Resources of Canada in collaboration with the Pulp and Paper Research Institute of Canada (now called FPInnovations) produced a benchmark for the energy consumption of North American P&P mills. This reference can help a mill position itself versus its competitors and compare its energy consumption in the various parts of the process to that of similar mills.

The main results of the survey are presented in table 2-1. The energy consumptions are normalized to a unit of production, the oven dried ton (odt) to facilitate the comparison.

Table 2-1 gives the average energy consumptions for a Kraft mill producing bleached pulp. Values were taken from 20 Canadian Kraft mills. The table highlights the large difference between the most efficient and the least efficient plants [2]. The disparity in efficiencies shows that there is definitely potential for improvement in most Canadian Kraft mills.

Table 2-1 : Average energy consumption and production for bleached Kraft pulp

	Electricity Consumption (kWh/ODt)†	Fuel Consumption (GJ/ODt)†	Thermal Energy Consumption (GJ/ODt)†	Thermal Energy Production (GJ/ODt)†	Net Thermal Energy Production (GJ/ODt)†
25th Percentile	455.20	27.72	12.71	16.19	3.60
Median	550.30	32.53	16.27	18.05	1.32
75th Percentile	633.80	34.12	18.51	19.79	– 0.22
Modern	370.00	NA	8.60	NA	NA

† The specific energy is determined from the sum of energies for the following areas in each mill: kraft pulping, kraft recausticizing, kraft evaporators, kraft recovery boiler and kraft bleaching. The specific energy is the total energy divided by the bleached kraft pulp production. The pulp production is expressed on an oven-dried basis.

The energy efficiency depends strongly on the processes and technology used, and on the mill's energy management and utilization strategy.

2.1.5 The biorefinery concept

The biorefinery is an industrial complex for the production of fuel, energy and various chemicals from biomass, by means of various specific processes [17]. This concept is very similar to oil refining through which combustible and various value-added products are manufactured. However, the biorefinery uses a renewable feedstock: lignocellulosic biomass. This biomass contains lignin, hemicelluloses and cellulose. These compounds are found in plant materials in varying proportions.

A biorefinery can exist as a standalone process or incorporated into an existing process as an integrated biorefinery. Implementation of the integrated forest biorefinery has significant advantages for both the P&P mill and the biorefinery. The infrastructures in place, the available manpower and the raw materials constitute an advantage to the P&P mill and make them good candidates as biorefinery receptors. The biorefinery is an effective way for the P&P mill to diversify its product portfolio and regain its economic prosperity. Figure 2-6 schematically shows the concept of the integrated biorefinery.

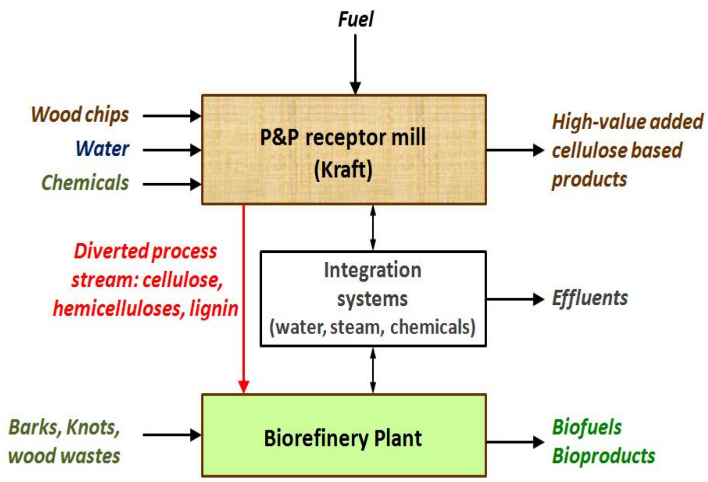

Figure 2-6 : Scheme of the integrated forest biorefinery [18]

The concept of the integrated forest biorefinery presented in figure 2-6 shows the material and energy streams exchanged between the processes. In the Kraft pulping process, only 42% of the woody biomass is converted to pulp and the rest (lignin and hemicelluloses) is combusted to produce energy for the process. This portion can be better utilized to increase the revenue margins of the mills. It can be converted into higher value products. Part of a process stream from the receptor mill rich in hemicelluloses, lignin or cellulose, could be diverted and fed to a converting biorefinery plant to produce value-added products. Kraft pulping is the prevalent pulp making process worldwide and is suitable for biorefinery integration because it is independent in terms of energy and material. The integration of the forest biorefinery process in P&P process permits the use of waste as inputs to one another and the use of common infrastructure to reduce the cost of both the pulp and paper and the biorefinery plants [19]. However, this implementation is subject to constraints and limitations. One constraint for the pulp and paper plant is high energy efficiency that ensures independence from fossil fuels. A prerequisite to the sustainability of the integrated forest biorefinery is a high level of efficiency of the receptor P&P mill in particular in regards to the consumption of steam and water. Before integrating the biorefinery, the receptor P&P plant must be optimized to provide enough energy to supply for the biorefinery demand. Enhancement modifications could be required for certain equipment of the Kraft receptor mill, before implementing the integrated biorefinery process.

2.2 Process Integration Techniques

Process Integration (PI) is an efficient approach that can be used to increase the profitability of paper mills through reduction of energy, water and raw material consumption and thereby, their operating costs. PI encompasses several methods that can be based on mathematics, thermodynamics or economics.

Process integration, combined with other tools such as process simulation, data reconciliation or life cycle analysis, is a powerful and efficient approach to systematically analyse the performance of an industrial process and understand the interactions between its various parts.

PI techniques serve to address many industrial issues such as debottlenecking of critical areas in a given process, utility system optimization, energy saving, and GHG emission reduction [20].

The PI techniques can be classified according to the approaches on which they are based. Thus, one can identify 3 types of PI for the design and optimization of heat exchangers networks:

- Conceptual approaches based on thermodynamic principles, better known as pinch analysis [21].
- Numerical approaches based on mathematical models.
- Hybrid approaches combining graphical and mathematical methods.

2.2.1 Pinch analysis

Pinch analysis is the most widely used PI approach, whereby it is possible to visualize a global picture of the energy use in the process. This method can be used to quickly identify areas of rule violations, which are symptomatic of energy inefficiencies in a process. Other more complex mathematical methods have been developed to optimize energy use in a plant, taking into account the specific constraints of each of the process components.

a) Thermal Pinch

Pinch Analysis is a structured approach to utility management. It is a standard tool to increase internal heat recovery. The purpose of pinch analysis is to maximize internal heat recovery within a process and to minimize the need for hot and cold energy supplied by utilities. It was developed at the beginning of the 1980's [22-24] and has been proven to achieve energy reductions. Pinch analysis significantly improves both process design and design process [25, 26]. Rather than complex mathematical methods, pinch analysis uses a simple concept. The principle is that the process is defined in terms of supplies and demands (sources and sinks) of commodities (energy, water, etc.). In that sense, composite curves are constructed and displayed in a temperature vs. enthalpy diagram (all possible heat transfers within the process). Figure 2-7 illustrates the pinch principle. The optimal solution is achieved by appropriately matching suitable sources and sinks.

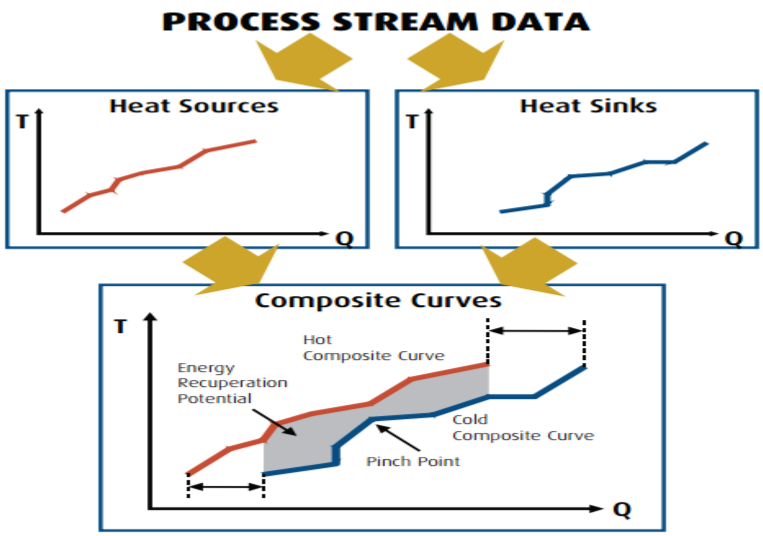

Figure 2-7 : Simplified schematic of the pinch analysis basic principles [20]

The composite curves constructed from the energy sources and sinks identify the potential savings. The pinch point represents the minimum temperature interval between the two curves. In old Canadian pulp and paper mills, the heat exchangers network was designed and installed without considering the pinch rules. Therefore, economically attractive energy savings can be obtained simply by respecting the pinch rules.

The application of pinch analysis to industrial sectors such as petrochemicals and pulp and paper can typically represent around 10 to 25% savings in energy consumption and around 25 to 40% in water consumption [20].

The main advantages of this method are the following:

• It is a graphical method that provides a visual approach to the phenomena, whereas most of the optimization methods are purely numerical.

• It reduces the investment and operating costs.

• Optimization can be performed before making assumptions about the network configuration.

b) Water Pinch

The integration of the water network was used primarily to serve the energy integration [27]. Originally, the 'Thermal Pinch' method has inspired a water pinch method to identify areas of violation of the pinch rules and reduce water consumption in the plant based on similar principles. A water consumption reduction would also reduce the overall energy consumption. The water pinch method provides a graphical solution for the potential reduction of water intake and effluents rejects.

The fundamental theoretical formulations for water pinch have been pioneered by Linnhoff. [24] Wang and Smith [28] and El-Halwagi [29]. These concepts have been successfully applied to a wide range of chemical process industries with typical fresh water savings in the range of 15-40% and wastewater savings of 20-25% [30].

c) Energy-Water Integration

Improving the energy efficiency of pulp and paper mills is strongly related to the proper management of water because water is the main medium of heat transfer, pulp washing and material transport. The larger the amount of water consumed and effluent produced within the mill, the larger the energy required for heating/cooling and pumping the process streams [31-34]. This strong correlation between water and heat underlines the necessity to develop a methodology that can address the simultaneous reduction of energy and water requirements [18].

Several authors have developed pinch-based methodologies investigating energy and water utilization. Schaareman *et al.* [35] applied in sequence and iteratively energy and water pinch analyses. However, thermal aspects were not taken into consideration to propose water reduction measures. Koufos and Retsina [30, 36] applied a similar study on a de-ink treatment facility. Savulescu *et al.* [37] suggested a combined procedure to simultaneously analyse water and energy consumption taking into consideration systems interactions. Brown *et al.* [31] developed a methodology combining pinch, exergy and mathematical optimization to identify and evaluate thermal efficiency of pulp and paper process. Mateos *et al.* [38-42] studied the complete process to determine the water reuse opportunities and analyse the impact on the overall thermal performance. The methodology has been applied to a Canadian Kraft mill. Performance indicators and the evolution of composite curves have served in the application of the method to monitor the process performance [18].

A pinch-based approach for a combined energy and water efficiency enhancement methodology has been developed by Keshtkar *et al.* [18, 32] which is an extension of the methodology developed by Mateos *et al.* [43] . Its application to three Canadian Kraft mills revealed over 26% of energy savings and over 33% of water reduction [18], which is far superior than engineering practice. An exhaustive report of the results obtained by the application of the methodology is found in the appendix B of this thesis, and is published in PAPTAC Journal in 2015.

2.2.2 Mathematical optimisation

In addition to the graphical methods, mathematical methods have been developed for energy and water optimisation and integration. An optimization problem consists of maximizing (in the case of power generation) or minimizing (in the case of energy use or production costs) an objective function, of n decision variables, subject to a set of constraints (mass or thermodynamic balance) expressed in the form of linear equations or inequalities. Several mathematical energy integration methodologies have been developed and presented.

Goortani *et al.* [44] used a mathematical optimization method to study the impact of the implementation of a cogeneration unit, along with other measures, to improve the energy efficiency of a Kraft mill. The results of their study showed a significant improvement in energy savings and a production of a considerable surplus of energy. Savulescu *et al.* [34] studied and developed a systematic method, based on the pinch tool for the energy integration and the identification of an optimal design of heat exchanger networks. Rafione *et al.* [45] developed a mathematical model to optimize the integration of energy and water networks in a green integrated Kraft forest biorefinery. Mathematical optimization for water and energy integration of

Kraft processes or Kraft integrated biorefineries is an interesting tool to identify potential savings. Its practical application is however complicated and is not part of the tool kit of mill engineers. This is its main limitation.

2.3 Process simulation

A thorough understanding of the physical or chemical phenomena and knowledge of related properties of the involved components are a prerequisite for process simulation. Process simulation is a model-based representation of a chemical, physical or biological process and unit operations, using a computer software. This computerized representation of a process enables engineers to perform optimization, integration or validation analyses and also to find optimal operating conditions. Hence, it is a useful tool to address many engineering issues. The use of process simulation plays a key role in developing an integrated approach to process design. It also saves time and money before the implementation of a real concept. This practice can assist engineers and mill operators with troubleshooting design, control, and revamping of unit operations. Many petrochemical and chemical industries have been using process simulations for these reasons. Many types of software have been used; one can name, for example, ASPEN Plus® for simulation of macroscopic unit operations and COMSOL Multiphysics® for microscopic and dynamic simulation of physical phenomena.

However, the simulation of a pulp and paper process is very different from petrochemical processes because of the nature of the reactions involved, the different phases and compounds interactions. Several softwares for pulp and paper process simulation are commercially available such as WinGEMS, BALAS or CADSIM. These Softwares operate either in continuous or dynamic mode and are specially designed to simulate the pulp and paper process. They include software modules representing the specific unit operations of pulping processes.

The simulation software used in this research study is CADSIM Plus, developed and distributed by Aurel Systems. CADSIM Plus is a specialized software, focused on P&P processes widely used by the forest industry in Canada.

2.4 Data reconciliation and gross error detection

Process simulation and data reconciliation are complementary tools with appreciable synergetic effects. The construction of a simulation that accurately represents the process configuration and operating conditions is preliminary to any process performance analysis. The objective of process simulation is to supply data for performance evaluation or process integration studies. However, a real pulp and paper plant is never in a true and rigorous steady-state; adjustment of operating conditions, change in the source of raw materials, equipment turnover, feed rate variations, or maintenance shutdown cause the system to constantly fluctuate, perturbing its steam, water and raw material consumption [41]. Therefore, measurements are needed to monitor the process efficiency, to verify that the operating conditions remain within required range, to ensure good product quality, and to avoid equipment failure or any hazardous conditions.

However, the measurements inherently contain errors, whether random or gross errors. Therefore, the mass and energy equations around unit operations often do not balance. Data reconciliation aims to adjust the measurements so that the energy and mass conservation laws are respected. Data reconciliation is essential for efficient development of coherent simulation models that supply reliable data.

Figure 2-8 displays the classification of process variables in a system and table 2-2 summarizes the basic fundamentals, necessary for the understanding of the concepts of data reconciliation and gross error detection.

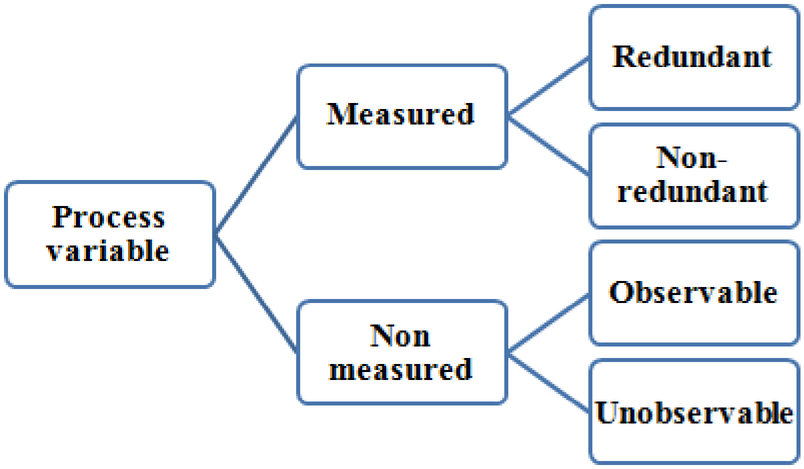

Figure 2-8: Classification of process variables

Table 2-2 : Definition of important data reconciliation parameters

Parameter	**Definition**
Random error	If a measurement of a process is repeated under identical conditions, the same value is not obtained. This is due to the presence of random errors, or 'noise' in the system. Random errors occurrence is governed by the probability laws. They cannot be predicted nor explained. They can be adjusted and their impact can be minimized with large sample sizes of observations.
Gross error	Refers to a deviation in a measurement that is not only due to randomness of occurrence. Probable sources are improper calibration of the measurement device, deterioration of the equipment or the device, wrong operating conditions, etc. A gross error has a magnitude and a direction (positive or negative sign), and does not follow the probability law. It is consistent and large number of observations does not eliminate its effect. It must be eliminated otherwise the conclusions of the analysis may be

	invalid.
Residual	The residual is the difference between any observation and its most probable value. The residual of balance of constraints is the remainder when the conservation laws are not conserved. The residual vector reflects the degree of violation of material ad energy conservation laws.
Observable variable	An observable variable is an unmeasured variable that can be estimated from measured variables through the process constraints.
Unobservable variable	An unobservable variable is an unmeasured variable for which no information is available.
Redundant variable	A redundant variable is a measured variable that can be estimated by other measured variables through process constraints, in addition to its measurement.
Non-redundant variable	A non redundant variable is a measured variable that cannot be estimated other than by its own measurement.
Process constraints	The model process constraints are typically mass and energy conservation laws.
Redundancy (spatial and temporal)	A measurement is spatially redundant if there are more than enough data to completely define the process at any instant in time. A measurement is temporally redundant if its past measurements can be used to estimate the current state. A typical case for a temporally redundant measurement is that, at the current sampling time, t, the true value of the process variable can be predicted by dynamic models, in addition to the raw measurement.
Observability	A system is observable when all the unmeasured variables can be estimated via process constraints and the available measurements.
Reconciliation feasibility	The reconciliation is possible only if the system considered is both observable and redundant. In other words, all the unmeasured variables can

	be estimated, and there is additional information (redundancy) to validate the computations, and adjust the redundant measurements.
Bilinear systems	Bilinear systems are a special case of non linear systems, in which non linear terms are constructed by multiplication of control vector and state vector such as: $y^T A_x$ = constant.
Level of confidence	A level of confidence is a measure of reliability of a statistical result. For a 95% (α=5%) confidence interval, the probability of observing a value outside of this area is less than 0.05.

Data reconciliation techniques have only been applied since recently to P&P [46]. In fact, in the P&P industry, it has been noted that there are few examples of large-scale simulations that are actually based on reconciled data collected from processes in operation [46]. Data reconciliation requires a large amount of data to solve the modeling equations. In spite of the abundance of information that can be acquired using process sensors, a considerable amount of additional measurements are still required to reach a satisfactory level of redundancy and thus, perform data reconciliation in an operating P&P mill. This is due to the fact that measurement devices in a P&P mill have not been placed to perform effective data reconciliation. In fact, P&P mills perform as few measurements as necessary to produce a product of constant quality and to estimate daily expenses and revenues. Jacob and Paris [46] presented an off-line data reconciliation technique for data calibration of a paper deinking process and a newsprint mill. Bellec *et al.* [47] used an on-line systematic method to improve data quality of real-time measurements of pulp and paper mills. However, no data reconciliation of a Canadian Kraft or pulp and paper mill has been published.

2.4.1 Data reconciliation: problem formulation

Data reconciliation is an optimization problem that aims to minimize the weighted sum of squared differences between the measured and the reconciled values under constraints that correspond to mass and heat balances. Mathematically, it can be formulated by the following constrained weighted least-squares optimization problem [48]:

$$\min_{x_i,u_j} \sum_{i=1}^{n} [\frac{y_i - x_i}{\sigma_i}]^2 \qquad (1)$$

In vector form, this equation becomes,

$$\min_{\mathrm{x}} \ (\mathrm{y}-\mathrm{x})^{\mathrm{T}} \ \ \mathrm{W}^{-1} \, (\mathrm{y}-\mathrm{x}) \qquad (2)$$

It is subject to the constraints:

$$g_m \left(x_i \, , u_j\right) = 0 \qquad (3)$$

The number of constraints in the model is m, and y is the measurement vector that can be written:

$$y = x + \varepsilon \qquad (4)$$

The vector x, is the vector of true values of the measurement variables, and ε is the vector of random measurement errors, that are normally distributed with zero mean and possess a covariance matrix W. The vector u is the vector of unmeasured observable variables that should be estimated by the reconciliation procedure. The (m) constraints correspond to mass and energy balances that must be satisfied, and are encapsulated in the term g_m.

Several methods presented in the literature have been developed to solve optimization problems. The complexity of the techniques depends strongly on the constraints imposed, which can be linear (case of global mass balances) or non linear (case of energy balances and individual component mass balances).

The analytical solution of the optimization problem under linear constraints, with all variables measured, is obtained by means of Lagrangian multipliers [49, 50], and is given by:

$$\hat{\mathrm{x}} = \mathrm{y} - \mathrm{W}\,\mathrm{A}^{\mathrm{T}}(\mathrm{AW}\,\mathrm{A}^{\mathrm{T}}\,)^{-1} \ \mathrm{A}\,\mathrm{y} \qquad (5)$$

Under the constraints:

$$\mathrm{Ax} = 0 \qquad (6)$$

The details of the mathematical development can be found in appendix A of the thesis. The incidence matrix (A) corresponds to the Jacobians of the constraints, and V is the covariance matrix of random errors as mentioned earlier.

If the constraints are nonlinear (the case of heat balances for instance), then they must be linearized. Several linearization methods are possible and available in the literature. The successive linearization is one of the most popular methods for data reconciliation applications [51]. The general principle of the successive linearization technique consists of using a Taylor expansion to the first order around the estimated values of the variables, and to iterate until an optimal point is obtained satisfying the non-linear constraints [51]. However, this method cannot treat inequality constraints, very common for dynamic reconciliation [51]. The SQP (Successive Quadratic Programming) method is an example of an algorithm that can solve a nonlinear system with inequality constraints [51]. The disadvantage of SQP methods is that they require longer computation time than successive linearization for steady state reconciliation [52]. The advantage of SQP technologies over the successive linearization method is that it allows the treatment of inequality constraints which can make the system converge towards more realistic values, since the number of constraints increases. Nevertheless, successive linearization using Taylor's expansion is the method recommended for bilinear steady state system.

Moreover, when the data set contains unmeasured variables (u), the solution can be obtained by the method of orthogonal QR factorization[3] developed by Crowe [53]. The incidence matrix (A) can be divided into two matrices: one contains the measured variables (A_x) and the other contains the non-measured ones (A_u), according to the following equation [49] :

$$A_x\, x + A_u\, u = 0 \tag{7}$$

A_x is the incidence matrix of the variables measured, and A_u is the incidence matrix of unmeasured variables.

According to Crowe's method [51], the unmeasured variables are first removed by multiplying both sides of equation (7) by a projection matrix, P, obtained by the QR factorization, so that:

$$PA_u = 0 \tag{8}$$

[3] QR factorization, in linear algebra, is a method for decomposition of the square matrix A, into a product A=QR of an orthogonal matrix Q and an upper triangular matrix R. QR factorization is often used to solve the linear least squares problems.

The reconciliation problem becomes:

$$\min_{x,u} \ (y - x)^T \ V^{-1} (y - x) \tag{9}$$

Under the constraints (from equation 7):

$$PA_x \, x \ = 0 \tag{10}$$

The projection matrix P is obtained by applying the method of QR factorization to the matrix A_u. The detail of the mathematical development of the QR factorization is presented in the appendix A of the thesis. The solution of the optimization problem is obtained by replacing the matrix A by PA_x matrix, in equation (5) [49]:

$$\hat{x} \ = y - W \, (P \, A_x)^T (P \, A_x \, W \, (P \, A_x)^T \,)^{-1} \, (\, P \, A_x \,) y \tag{11}$$

Once the measured variables are reconciled, the unmeasured variables can be estimated using the following equation:

$$\hat{u} \ = \ -(A_u^T A_u)^{-1} \ (A_x \ \hat{x}) \tag{12}$$

In the reconciliation problem, only the redundant measured variables are adjusted. The non-redundant measurements and the observable variables are eliminated from the reconciliation problem.

Observability and redundancy:

For economic and technical reasons, not all variables in a mill are measured. In fact, in a real operating mill, there are only measurements that are necessary to control the process. Data reconciliation is only possible if the system under study is both observable and redundant. An observable system is a system of which all the unmeasured variables can be estimated via process constraints and available measurements. An observable system is redundant when at least one additional measurement is available to validate the computations. A redundant system is said to have a positive global redundancy. The number of global redundancy (GR) is obtained by substituting the number of unmeasured variables (j) to the number of process equations (m), as shown in the following equation [51]:

$$GR = m - j \tag{13}$$

Two situations may arise, depending on the value of the number of the computed overall global redundancy; when, $GR \geq 0$, the system can be solved, and for $GR<0$: the system remains undetermined. This situation occurs when there are less measured variables than unknown variables linked by physical and thermodynamic relations.

Moreover, as explained in table 2-2, there are two types of redundancy [51]:

- Spatial redundancy which represents the physical distribution of measurements in the plant.
- Time redundancy which represents the measurement of the same variable at different times.

Both time and spatial redundancies are needed to perform data reconciliation.

Variable classification:

It is important to classify the variables that describe the system studied, in order to solve the reconciliation problem and ensure that the system is observable and redundant. Several strategies have been formulated for performing process variable classification. These strategies may be divided into 2 major groups. In a group the concept of graph theory is applied to achieve the categorization, and in the other group matrix ordering techniques and computations are used [54]. Graph oriented techniques have been developed by Vaclavek [55-57], Mah *et al.* [58-61] and Meyer *et al.* [62]. Vaclavek [56] first defined the concept of observability and redundancy by graph representations and classified global flows in a process according to this concept. Later, Kretsovalis and Mah [63, 64] and Meyer *et al.* [62] developed a variant and simplified method of the graph theory applicable for bilinear systems. However, these techniques require an extensive analysis of the process graph and its derived subgraphs making them complicated for practical applications. A more detailed explanation on the application of the graph theory can be found in appendix A of the thesis.

Equations-oriented approaches were developed by four main groups of researchers: Romagnoli and Stephanopoulos [65], Crowe [53], Joris *et al.* [66], and Madron *et al.* [68]. The majority of mathematical variable classification procedures are based on the manipulation of the occurrence matrix of the process, which correspond to the matrix of balance equations. Romagnoli and Stephanopoulos [65] proposed a classification procedure based on the application of an output set assignment algorithm to the occurrence submatrix of unmeasured variables associated with linear or nonlinear model equations. Crowe *et al.* [67] proposed the utilization of the projection matrix P to eliminate the non-measured variables from linear systems and later extended this method to bilinear systems. Joris and Kalitventzeff [66] developed a procedure for the classification of variables that is accomplished by permuting rows and columns of the occurrence matrix corresponding to the Jacobian of the model equations. However, this mathematical procedure fails to detect the undeterminable (unobservable) variables. Madron *et al.* [68] proposed a classification procedure based on the conversion into the canonical form of the matrix associated with linear or linearized plant model equations. This is extensively described in the monograph by Madron [68]. Crowe's method for variable classification using the QR factorization and the projection matrix P is recommended for bilinear system at steady state [51].

2.4.2 Gross error detection

Measurements inherently contain random errors due to noise of sensors that cause them to violate process constraints. Data reconciliation is meant to correct these errors [69]. However, gross errors due to a sensor failure or equipment malfunction should be detected first. This is usually done by verifying that all measurements remain within acceptable upper and lower bounds. To do so, statistical tests are developed to detect, identify and locate the gross errors. The basic principle of gross error detection is derived from the identification of outliers by statistical techniques [69]. Figure 2-9 reproduced from Narasimhan and Jordache [51] illustrates graphically the most common types of instruments faults: bias, complete failure, drifting and precision degradation.

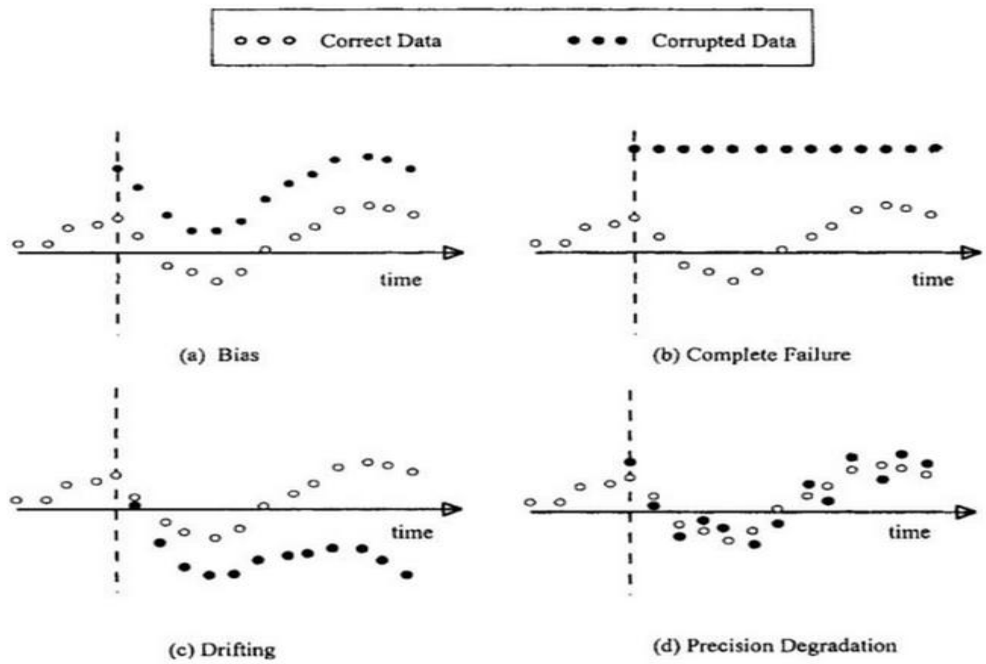

Figure 2-9: Instrument types of faults [51].

The random errors inherently present in measurements are assumed to follow a normal distribution. Thus, the normalized errors ($(X-\mu)/\sigma$) also follow the normal distribution. Normalized errors should fall inside a ($1-\alpha$) confidence interval at a chosen confidence level α. Any value of a normalized error which falls outside that confidence region is declared an outlier or a gross error.

The most commonly used statistical techniques for detecting gross errors are based on hypothesis testing. In gross error detection, the null hypothesis H_0 means that no gross error is present in the data set tested, and H_1 means that at least one gross error is present.

The result of the statistical test that assesses of the presence of a gross error is compared to a pre-specified threshold value. The null hypothesis is rejected or accepted, respectively, depending on whether the statistical test exceeds the threshold or not. The threshold value is also known as the test criterion or the critical value of the test.

The outcome of the statistical test is not perfect, two types of detection errors, called type I and type II errors may occur. Type I errors (also called false alarm) are errors detected when in fact no gross error is present. Type II errors correspond to the presence of gross errors not detected from the test. Therefore, the test criterion can be selected so that the probability of type I error is less than or equal to a specified value of α referred to as significance level for the statistical test. However, no statistical test is guaranteed to successfully identify and locate all gross errors [51]. This is the main limitation of statistical tests. Therefore, it is recommended to use more than one statistical test for the detection of gross errors.

Statistical techniques:

Assuming a linear constraint model:

$$Ax = c \tag{14}$$

Where A is the matrix of linear constraint and c=0, for linear constraints.

The random errors are assumed to be normally distributed with known variance and covariance matrix W.

Then:

$$r = Ax - c \tag{15}$$

where r is the vector of balance residual. In the absence of gross error, r follows a multivariate normal distribution with zero mean and a variance-covariance matrix V, [51] given by:

$$V = \text{cov}(r) = A\,W\,A^T \tag{16}$$

Therefore, under the null hypothesis H_0, r~N(0,V), in the presence of gross errors, the elements of the residual vector r reflect the degree of violation of process constraints (material and energy conservation laws). The V matrix contains information on the process structure (matrix A) and on the measurement variance-covariance matrix (matrix W). Therefore, the two quantities r and V can be used to construct statistical tests which can detect the presence of gross errors.

Global Test (GT):

Several authors such as Madron [68], Ripps [70] and Almasy *et al.* [71] suggested the use of a global chi-square (χ^2) statistical test constructed from the observed discrepancies in the constraints (the balance residual vector r), given by:

$$\gamma=r^T V^{-1} r \quad (17)$$

Under H_0 (in the absence of gross error), the test follows a χ^2 distribution with υ degrees of freedom, where υ is the rank of matrix A (rank of matrix A is equal to the number of process constrains). The test criterion (or threshold) is chosen at $\chi_{1-\alpha,\upsilon}{}^2$, with a chosen significance level α. Then H_0 is rejected and a gross error is detected in the data set tested if $\gamma \geq \chi_{1-\alpha,\upsilon}{}^2$. The choice of the significance level α (and therefore the test criterion) ensures that the probability of type I error is less than or equal to α [51].

The difficulty of this global test is that it detects the presence of gross errors but it does not locate the sources of these errors. Then, an additional scheme must be used [67]. Moreover, this global test does not determine the number of gross errors present.

<u>The Constraint or Nodal Test (NT):</u>

Reilly and Carpani [72] and Mah *et al.* [58] independently proposed performing a separate test on each process constraint residual (r_i):

$$\gamma = z_{r,i} = |r_i| / \sqrt{V_{ii}} \quad (18)$$

Under H_0, when no gross error is present, the result of the statistical test ($z_{r,i}$) follows a standard normal distribution N~ (0,1) [51]. If the result of the statistical test $z_{r,i}$ exceeds the test criterion ($Z_{1-\alpha/2}$, with a level of significance α in a two-sided-test), a gross error is detected. Since the same test criterion is used for all constraints, the probability that the test is rejected when no gross errors are present increases. In other words, the probability of type I error is higher than the value of α. Type I error probability could be reduced by modifying the criterion for each constraint. A modified level of significance β is used for each constraint [51], such as $\beta=1-(1-\alpha)^{1/m}$. The test criterion for each constraint becomes $Z_{1-\beta/2.}$

Crowe [53] developed and introduced a slightly modified form of the constraint test, which has the maximum power[4] to detect the presence of gross errors and is given by:

$$\gamma = Z_{r,i}^{*} = z_{r,i} = |V^{-1} r_i| / \sqrt{V_{ii}} \tag{19}$$

The test criterion is chosen to be the same as in the case of the standard constraint test. However, if there is a gross error, this maximum power test has a greater probability to detect it.

The application of this test is limited by the assumption that the gross errors in different streams incident at a given node (entering or leaving) do not cancel out. Because of this, this test assumes one error at a time.

The Measurement Test (MT):

Mah and Tamhane [60] proposed a more direct approach for gross errors detection. The statistical test they proposed is based on the measurement adjustments (a) rather than on the constraints residuals (r). The measurement adjustment is the difference between the value of the measured variable and its reconciled estimate as:

$$a = y - \hat{x} \tag{20}$$

The reconciled estimate $\hat{x}$ is obtained by the reconciliation optimization solution. Using the solution for $\hat{x}$, the measurement adjustment can be rewritten as follows:

$$a = \mathrm{W} A^{T} V^{-1} r \tag{21}$$

The variance-covariance matrix of the measurements adjustments is then calculated by:

$$\ddot{W} = cov(a) = \mathrm{W} A^{T} V^{-1} \mathrm{W} \tag{22}$$

Under H_0, the measurements adjustments follow a normal distribution N~ (0, $\ddot{W}$).

Then, the measurement adjustment statistical test given by:

$$z_{a,j} = \frac{|a_j|}{\ddot{W}_{JJ}} \tag{23}$$

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[4] A maximum power is the maximum probability of detecting a gross error.

also follows a standard normal distribution N~(0, 1), under H_0. The limitation of this test is that it assumes one error at a time, and therefore, ascribes the probability of presence of an error entirely to one measurement, which may amplify the magnitude of the gross error.

The Generalized Likelihood Ratio (GLR) Test:

The generalized likelihood ratio test (GLR) is based on the maximum likelihood ratio principle used in statistics. Narasimhan and Mah [73] were first to propose the use of GLR test for gross error detection. It is the ratio of the probability of occurrence of a gross error (H_1) over the probability of its absence (H_0), and can be written as follows:

$$\gamma = sup \frac{\Pr\left(f(y)|H_1\right)}{\Pr\left(f(y)|H_0\right)} \tag{24}$$

f(y) is the normal density function of the measurement x, and the term *sup* indicates the maximum of the function. The test (equation 24) can be simplified, as follows [74]:

$$\gamma = \left\{\frac{1}{1+(\frac{1}{\mathrm{n}-1})(\frac{\bar{\mathrm{y}}-\mu_0}{\mathrm{s}^2/\mathrm{n}})^2}\right\}^n \tag{25}$$

With n, is the number of samples in the measurement, $\bar{y}$ is the average value of the sample, μ_0 is the true mean, and s^2 is the sample standard deviation [75].

Multiple gross error detection:

Multiple gross errors detection, identification and estimation, have been the object of several studies in the last twenty years. All techniques developed for multiple gross errors detection and identification can be broadly classified as either simultaneous or serial strategies [76]. Simultaneous strategies identify on a single iteration all measurements whose statistical tests exceed the test criterion. This could be done through GLR test or measurement elimination strategy. The GLR test has been proved to be similar or equivalent to the global test followed by the measurement test. The GLR method attempts to identify as few gross errors as necessary to accept the null hypothesis (H_0). However, it hasn't been much used because of the large number of combinatorial alternative hypotheses to be tested for which a statistical test has to be performed. This method has been investigated by Serth *et al.* [77] and has been found to result in too many mispredictions because of the smearing effect causing a good measurement to exceed a test criterion if it is related, through a constraint, to a measurement containing a gross error. Serial strategies use the same approaches through several iterations. Many algorithms have been developed for that purpose. A possible solution to avoid the smearing effect is to perform multiple gross error detection of a combination of two or more independent variables (or independent constraints equations). However, the difficulty of doing so in real operating processes is the strong correlation between variables, and therefore, their inter-dependence, which makes the computations of probabilities tests for gross errors tedious, and the formulation of a probability function complicated.

2.5 Exergy analysis

The term "exergy" is used to describe the combination of energy quantity (which is conserved according to the first law of thermodynamics) and energy quality (which is consumed according to the second law of thermodynamics). Unlike conventional energy analysis that is usually mainly based on the first law of thermodynamics, exergy analysis relies on the first and the second laws of thermodynamics. It takes into account the properties of the system's environment and considers the energy conversion stages in the process operation where the quality of energy is degraded. The fundamental link between energy and exergy is the entropy. Entropy is an extensive property of a system and represents the amount of energy in a system that can no longer produce work [78]. The second law of thermodynamics states that the entropy of a real system increases inevitably and it cannot be reduced back to its initial state [79, 80]. Exergy as defined by Szargut [81] is the maximum amount of work that can be produced by bringing a process stream in thermal, mechanical and chemical equilibrium with its environment by a series of reversible operations. However, all real processes are irreversible with the consequence that exergy is destroyed due to entropy generation. Therefore, unlike energy, exergy is not balanced for real processes. For this reason, the exergy and energy analyses should be investigated differently.

The exergy of a system or a stream is the sum of the contribution of all its forms of exergy; potential, kinetic, thermal, chemical and electrical, and is completely determined by its temperature, pressure and composition in regards to a reference state.

$$\mathrm{Ex_{tot}} = \mathrm{Ex_p} + \mathrm{Ex_k} + \mathrm{Ex_{th}} + \mathrm{Ex_{CH}} + \mathrm{Ex_{elec}} \tag{26}$$

The reference state (temperature, pressure and chemical composition) is usually the environment in which the system operates [82, 83]. From a theoretical standpoint, the reference environment must be in thermodynamic equilibrium, and therefore, with no usable energy [84].

Thermodynamic analyses based on both energy and exergy efficiencies have been of scientific interest for several decades [85].

Exergy efficiency concepts have been introduced first by Grassman in the 1950' [86]. He expressed the exergy efficiency as the sum of all the exergy input streams, considered as useful exergy, over the sum of all the exergy output streams, also considered as useful exergy as expressed by:

$$\eta = \frac{\sum \mathrm{Ex_{out}}}{\sum \mathrm{Ex_{in}}} \tag{25}$$

In reversible processes with no exergy destruction, this definition always gives 100% efficiency. In real processes, on the other hand, exergy is destroyed. Thermodynamic efficiency of processes decreases as exergy is destroyed. Ultimate efficiency is achieved only at equilibrium (reversible process), i.e. infinitely slow process which is not a practical engineering option. Part of the exergy output from the system may be dissipated into the environment as sewered wastes or stack gases emissions. This exergy lost to the environment is no longer used by subsequent processes, therefore it is more appropriate from an engineering point of view and from the standpoint of downstream operations to consider the exergy that remains utilizable rather than the total output, and accordingly the definition of the efficiency by Grassman, is not best suited for real industrial applications. Fratzcher [87] introduced a slightly different exergy efficiency definition, that considers the exergy of output streams of products rather than the total exergy:

$$\eta = \frac{\sum Ex_{product}}{\sum Ex_{in}} \tag{27}$$

The purpose of an exergy analysis is to identify areas with poor efficiencies and propose enhancement measures that reduce the exergy destroyed and lost in the process. Exergy analysis has been largely applied in the petrochemical industry [88-90]. However, in the P&P industry there are few examples analyzing a complete mill [91], or specific sections [92-94]. Gong *et al.* [95] presented an exergy analysis based on a simulation of a Swedish pulp and paper mill. In their studies, they demonstrated that the exergy contents of the streams are much less than their energy contents. The exergy analysis of the Swedish pulp and paper mill showed that the largest exergy losses appear in the boilers and the heating processes are highly inefficient. Similarly, Regulagadda *et al.* [96] presented an exergy and energy analyses of a thermal power plant. Their study showed that the major losses of exergy occur in the boiler, whereas when energy analysis is performed, the condenser is shown to be the least efficient. These results highlight the significant difference between energy and exergy analyses. Sorin and Paris [90] also presented an integration of pinch analysis to thermodynamic analysis of a process by means of an exergy load distribution method and demonstrated its effectiveness in improving systems by applying it to a hydrogen production unit by methane reforming.

Exergy has been proven to be a valuable tool for identifying thermodynamically inefficient areas and improving the overall process performance. However, pinch and exergy analyses have been put in competition by some authors. Linnhoff and Alanis [23] argued that pinch analysis produced more meaningful targets by considering design information. Gaggioli *et al.* [97], on the other hand, established that pinch analysis can only be used for designing HEN and, since it is a systematic approach, many improvement options can be overlooked by this analysis alone. Conversely, exergy analysis identifies possibilities for improvement. In fact, their fields of action are different but complementary.

2.6 Dimensional analysis

Dimensional analysis is a powerful analytical technique to study physical and thermodynamic processes; it facilitates the understanding of physical phenomena; simplifies the analysis procedure and enables efficiency diagnostics. It produces a complete set of dimensionless numbers that describe a physical process and outline the conditions under which the process operates. Buckingham [98] first introduced a stepwise procedure for the development of non dimensional numbers that describe a given process. The Buckingham Pi (Π) theorem derives its name from Buckingham's use of the symbol (Π) for the dimensionless variables in his original 1914 paper [99]. Since then, considerable efforts have been devoted to developing dimensionless numbers to characterize unit operations performance in a concise way. Several dimensionless numbers have thereby been formulated. Examples are the Reynolds number (Re), to characterize the kind of flows in all types of fluid dynamic problems, the Froude number (Fr), for modeling flow with a free surface, Nusselt (Nu), Biot (Bi) and Peclet (Pe) to describe heat transfers, or the Carnot coefficient (η) for energy efficiency, to only name a few. Several authors [100-111] used dimensionless numbers to evaluate the performance of chemical engineering unit operations. The dimensionless groups are then interpreted on the basis of a pertinent operating ratio (heat or mass flux for example). Attempts have been made to produce empirical correlations that combine different dimensionless numbers, applicable to a range of operating conditions. Balocco [103] proposed an energy efficiency analysis for cooling and heating buildings based on dimensional analysis. Arora and Potucek [112-114] suggested the use of dimensional numbers such as Biot and Peclet to evaluate the performance of displacement washing operations. Brenner [114], Mcdonough *et al.* [115] and Jain *et al.* [116-118] used dimensionless numbers to evaluate the performance of the washing and the bleaching process operations. Nevertheless, no dimensional analysis of the complete Kraft process equipment has been published.

The formal most common tool for dimensional analysis is the Buckingham's II (or Pi) theorem, as mentioned earlier. It consists of a stepwise procedure, described below [101]:

1. Identification of independent variables (n):

$$Q_0 = f(Q_{1,}Q_2, Q_3, \dots \dots, Q_n) \tag{29}$$

This step consists of identifying a complete set of relevant independent variables. A set $Q_{1,}Q_2, Q_3, \dots \dots, Q_n$ is complete if once the variables are specified; no other variable can affect the value of Q_0. Variables are independent, if the value of each of them can be adjusted individually without affecting the value of any other. This step is the most important; it requires a thorough analysis of the operation under study. Assumptions can be made to avoid unnecessary details that can hinder the analysis.

2. Dimensional considerations; list of independent variables (m):

   This step consists of listing the dimensions of the independent variables $Q_{1,}Q_2, Q_3, \dots \dots, Q_n$ according to a chosen system of units.

3. Identification of a dimensionally independent subset:

   This step consists of selecting from the complete set of physically independent variables $Q_{1,}Q_2, Q_3, \dots \dots, Q_n$, a complete dimensionally independent subset $Q_{1,} \dots . Q_k$, $k \leq n$ and expressing dimension of each of the remaining independent variables $Q_{k+1,} \dots . Q_n$ and the dependent variable Q_0 as a product of powers of $Q_{1,} \dots . Q_k$.

   The subset $Q_{1,} \dots . Q_k$ of the set $Q_{1,} \dots . Q_n$ is dimensionally independent if none of its members has a dimension that can be expressed in terms of the dimensions of the remaining members. It is complete if the dimensions of the remaining quantities $Q_{k+1,} \dots . Q_n$ of the full set can be expressed in terms of the dimensions of the subset $Q_{1,} \dots . Q_k$.

   The dimensional subset $Q_{1,} \dots . Q_k$ is assembled by trial and error. The number k is unique to the set and cannot exceed the number of the base dimensions (k=≤m).

4. Obtaining the different equations to form the dimensionless numbers:

   Having chosen a complete dimensionally independent subset $Q_{1,} \dots . Q_k$, the dimensions of Q_0 and of the remaining quantities $Q_{k+1,} \dots . Q_n$ can be expressed in terms of the dimensions of $Q_{1,} \dots . Q_k$.

5. Solving for algebraic equations to obtain the powers of the dimensionless numbers:

6. Write the final result of the dimensional analysis

   This step consists of writing all the dimensionless numbers in the form,

$$\Pi_0 = f(Q_{1,} \dots . Q_k;\ \Pi_1 \dots \dots \Pi_{n-k}) \tag{30}$$

2.7 Equipment performance analysis (EPA)

Process integration techniques such as pinch analysis and mathematical optimization methods are based on the implicit assumption that the unit operations of a process operate efficiently. In practice, this is not always the case. Therefore, it is important to evaluate the performance of the equipment and unit operations in place before undertaking any optimization of a process.

The common way to evaluate the performance of equipment and unit operations is by means of specific key performance indicators (KPI). The use of indicators as a calibration tool is a common practice to measure the variability and correct the functioning of a process. Key performance indicators, when used efficiently can identify the areas and equipment that have savings opportunities.

One tool that is mentioned in the literature is the comparison of energy, water and electricity consumption normalized to the production rate of a mill, with the Canadian average and best practice mills. This lead to a preliminary identification of inefficient departments and further analysis is required to pinpoint the equipment causing the inefficiencies.

Lang and Gerry [119] proposed indicators to monitor process control systems and identify periods where control loops are outside the normal mode or when they oscillate. These indicators identify areas with significant deviations from target points (energy or material consumption for example) but do not provide information on what is causing these deviations. Similarly, Buckbee [120] defined indicators as the ratio between the setpoint and the actual targets achieved. The challenges that are associated with the wide variations in energy savings led the industries to implementing intensive monitoring. Van Gorp *et al.* [121] proposed a strategic method for utility distribution and energy management based on metrics for energy consumption per unit of production. The metrics are compared to the goals set for the projects on the energy consumption reduction and a mathematical relationship is used to monitor the consumption (compared to the targets). Retsina [122] proposed a similar methodology by adding a real-time monitoring of these indicators. Sivill and Ahtila [123] proposed the use of performance indicators that take into consideration the logistic and productivity periods of the mill based on their business strategy. The indicators proposed consider the paper production rate, the overall energy consumption and the economic parameters of the mill [123]. They also [124] developed a software to control these indicators. However, no work has been published on a complete structured and systematic approach for equipment performance analysis of a Kraft pulp process, by means of key performance indicators (KPIs).

Energy savings can be achieved by modifying operating conditions and by project identification [3]. Enhancement of the process, such as tuning boilers, checking appropriate insulation thickness, identifying and repairing steam traps, identifying streams that are cooled down and heated, and monitoring excess furnace air, can also produce energy savings [125]. However, the diagnostic and improvement projects, based on the available key performance indicators, depend on the expertise and experience of the mill managers, and also on their knowledge of the system and equipment. They do not provide direct information on what is causing the inefficiency, whether it is wrong operating conditions, or equipment condition deterioration. Therefore, new adapted key performance indicators should be formulated, for the Kraft process equipment, to facilitate the diagnostic of the causes of inefficiencies in unit operations.

2.8 Synthesis of literature review

2.8.1 Summary of literature review and scientific gaps

Energy efficiency analysis is the object of many studies. However, the literature review has highlighted a number of scientific gaps.

A recurrent problem in published examples is the lack of explanation or information on how the data, used for all analyses, are gathered or treated. The analyses are often based on computer simulations. The simulation models are generally not based on real reconciled mill data. There is no incentive in seeking to optimize a model, when it does not match the actual behavior of the real plant. A representative model based on reconciled data is a prerequisite step to any optimization or evaluation work.

Another problem is that process integration techniques implicitly assume that unit operations and equipment in place operate efficiently or as intended. In reality, this is often not the case. Equipment performance analysis is a necessary step prior to undertaking any integration measure.

This prerequisite step of equipment performance evaluation is usually either simple or nonexistent. There is no systematic or strategic methodology for a complete equipment performance analysis. Also, the key performance indicators available and used are not well suited to efficiently identify and diagnose the causes of inefficiencies in a mill, in terms of process operation performance or energy and material utilizations.

A pulp and paper mill contains a number of recycling loops that increase process interactions and make conventional pinch analysis or process integration techniques ill-suited. These techniques are applied to tackle energy efficiency without regard to the interactions in the complete process, thus failing to address the problems or the entire process including interactions. An equipment performance analysis, when strategically developed and applied, should take into account both the specific operating conditions of a unit operation and its interactions with other units of the process.

Exergy analysis is a valuable tool to evaluate the efficiency of a process. However, it has not evolved to a systematic method, such as the Pinch Analysis or the Water Pinch and has not been applied on a real Canadian Kraft mill, in combination with other tools for equipment performance analysis. P&P mills are driven by steam, water and chemicals which make them suitable for exergy studies. Traditional energy studies only consider thermal energy. Exergy analysis considers all forms of energy as well as the internal energy of the matter that is the chemical exergy.

The summary of the literature review leads to the formulation of the specific objectives to be observed in order to achieve the main objective of the thesis. The specific objectives are to:

- Develop performance indicators adapted to the Kraft process equipment for energy and matter.
- Identify poor performing areas and diagnose the causes of inefficiencies.
- Propose improvement projects to address the inefficiencies.

2.8.2 Overall methodology approach

To perform a complete equipment performance analysis, the overall unified methodology shown in figure 2-10 has been developed and applied. It consists of 6 main stages. The first step of the methodology is the development of a coherent model simulation that represents the long term average steady-state of the process. To do so, real mill data collection, gross error detection and data reconciliation have been performed. The results of the gross error detection strategy and data reconciliation identify strongly adjusted variables and highlight the processes suspected of having poor performances (an overconsumption or energy or water for example is asymptomatic of poor efficiency). Data reconciliation produces a congruent set of data that represent the long term average steady-state, based on mass and energy balances of Kraft unit operations. Exergy analysis of individual unit operations and of entire sections of the process has been performed. This analysis helps to identify poor energy performance areas.

Data reconciliation and exergy analysis help target problematic areas. A list of suspected inefficient equipment is constructed. Additional specific key performance indicators are developed to characterize and describe the process efficiency of the listed suspect equipment through a thorough and detailed dimensional analysis. A synthesis of improvement projects is then performed. A list of priority improvement projects are proposed and recommended to the case study mill in order to improve their overall efficiency.

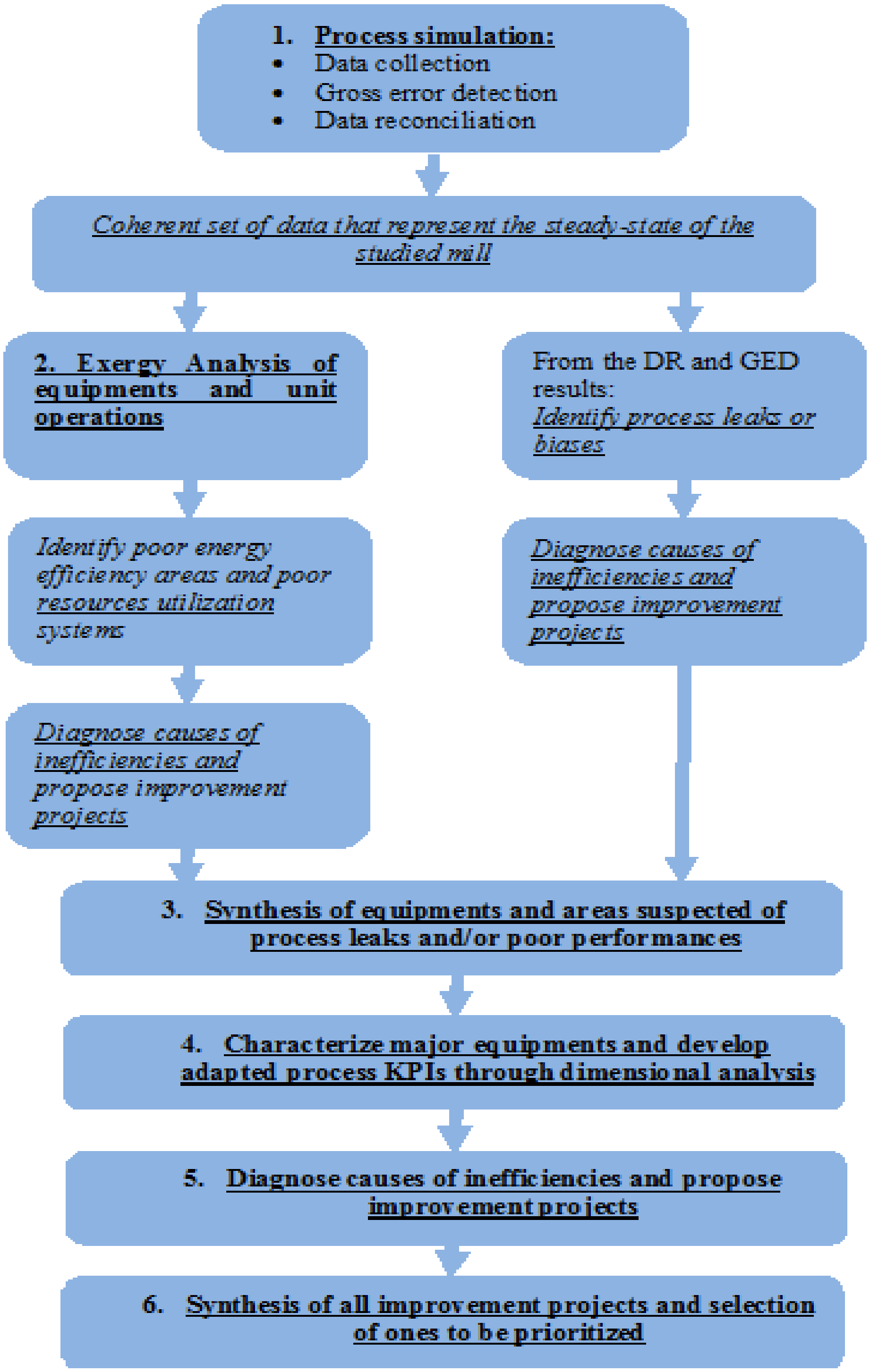

Figure 2-10 : Overall methodology

CHAPTER 3. ARTICLE 1: DATA RECONCILIATION AND GROSS ERROR DETECTION OF AN OPERATING CANADIAN KRAFT MILL

3.1 Presentation of the article

This paper has been submitted to the Computer and Chemical Engineering Journal. The application of data reconciliation and gross error detection technique to an operating Kraft mill is presented. The combinations of several statistical techniques have been used to efficiently identify and locate the gross errors. The results of the reconciled data and the gross error detection strategy have been analyzed to target and locate errors and identify the inefficient areas of the mill. The difficulties of applying data reconciliation and gross error techniques to a real Kraft mill have been highlighted.

3.2 Abstract

In this paper, the application of data reconciliation and gross error detection to an Eastern Canadian Kraft mill is presented and discussed. The reconciliation problem was developed from global mass and energy balances, and was solved via successive linearization. The new approach developed was tested using plant data. The presence of gross errors was determined using a new strategy that combines four successive statistical tests: the normal density test, the global test, the combined procedure and the generalized likelihood ratio (GLR) test. The algorithm and code for gross error detection and data reconciliation strategies were developed and solved using MATLAB®. The gross error detection strategy identified the sources of errors, computed their magnitudes, and corrected the corrupted measurements. The data reconciliation pointed the process areas which are strongly adjusted (± 25% adjustment). Such adjustments suggest a process operation problem, and the unit operations suspected of having poor performances were highlighted.

Key words: Kraft process, data reconciliation, gross error detection, global test, nodal test, generalized likelihood ratio test.

3.3 Nomenclature:

A	Incidence matrix, Jacobians of the process model constraints
A_u	Incidence matrix of unmeasured observable variables
A_x	Incidence matrix of measured variables
a	Vector of the adjustments of the reconciled variables
DR	Data reconciliation
g_m	Function of the process constraints
GED	Gross error detection
GLR	Generalized likelihood ratio
H_0	Null hypothesis, no gross error is present
H_1	Alternative hypothesis, at least one gross error is present
m	Number of process constraints
N	Number of observations
n	Number of variables
P	Projection matrix, obtained from QR factorization
Q_1, Q_2	Q Matrices obtained from the QR factorization of matrix A, qr(A)=QR
R_1, R_2	R Matrices obtained from the QR factorization of matrix A, qr(A)=QR
r	Vector of constraints residuals
s	Standard deviation
u	Vector of the observable variables
V	Variance matrix
W	Covariance matrix of the error
x	Vector of the true variables
y	Vector of measured variables

Greek

α	Confidence level
β	Power confidence level
ε	Vector of random errors
μ	Average value of a sample
σ	Standard deviation

γ Result of the statistical test

χ^2 Chi-squared statistical test

Superscript

$\bar{}$ Average value

^ Reconciled value

T Transpose

3.4 Introduction

The performance analyses of pulp and paper mills are usually based on simulations that represent the mills at an average presumed steady state. However, a real Kraft plant is never in a true and rigorous steady-state; local adjustments of operating conditions, feed rate variations, operational drifts or deviation, fluctuations of a measurement and malfunction of monitoring equipment, cause constant fluctuations of the mass and heat flow rates. Therefore, performance evaluation results based on these process simulations may present a bias. On the other hand, the development of a new representative simulation can be a tedious task, and is often developed by trial and errors and does not take into account the real fluctuations of the mill. Due to errors in the measured data or assumptions made due to a lack of necessary data, the simulation might not be the best representation of the long term average steady-state of the real process. Therefore, the development of a structured procedure to generate a reliable set of data that represent the long term average steady-state of the mill will be of great help for process simulation construction.

Data reconciliation is essential for process performance follow up and simulation model development and calibration. Based on measurement redundancy, it is recommended as a preliminary step to process simulation. It should be a common practice to start with data reconciliation in order to generate a congruent and reliable set of data before undertaking any performance evaluation.

In a Kraft mill, a large number of variables are measured and archived on a daily basis for the purpose of process control and performance evaluation. These measurements are subject to both random and gross errors, so that they generally do not satisfy the conservation laws and other process constraints. Therefore, the measurements need to be adjusted in order for them to obey the conservation laws and any other constraints imposed upon them. This procedure is known as data reconciliation (DR). It is an optimization process that aims to minimize the overall correction (adjustment), measured in the weighted least squares term, to satisfy the system constraints.

A good overview of the available methods for data reconciliation is given in Mah [1]. Work and development on data reconciliation procedures and gross error detection techniques for industrial processes have been done, notably by Ripps [2], Reilly and Carpani [3], Swenker [4], Vaclavek [5, 6], Mah *et al.* [1, 7, 8], Romagnoli and Stephanopoulos [9], Stanley and Mah [10, 11], and Mah [7]. Reviews of the published work have been presented by Hlavacek [12] and Mah [13], and Ham *et al.* [14] have reported on industrial applications of data reconciliation techniques to improve the quality of measured plant data [15].

The reconciliation techniques developed have been applied in various fields including chemical and metallurgic processes. Tamhane and Mah [16] presented a thorough review of data reconciliation and gross error detection methodologies proposed in the chemical engineering literature, and those methodologies were illustrated by examples. They presented the data reconciliation as based on weighted squares estimation under constraints and detection of gross errors based on the residuals obtained in the reconciliation step. Data reconciliation techniques have also been applied in the pulp and paper industry for various off-line and on-line applications. For example, Jacob and Paris [17] used data reconciliation techniques for data calibration of the simulation of an integrated newsprint mill, and suggested redundancy and sensitivity analysis for the mill sampling protocol. Bellec *et al.* [18] used an on-line systematic method to improve the steady-state data quality of real-time measurements. However, no previous work has been published on the application of data reconciliation to a real operating Kraft mill.

The successful application of the data reconciliation by means of weighted least squares solution relies on the assumption that errors are normally distributed with zero mean, in other words, not containing gross errors. In practice, process data do contain gross errors. Such errors will affect the reconciliation and adjustment by smearing effect, and should be detected. Previous publications by Reilly and Carpani [3], Almasy and Sztano [19], and Mah *et al.* [8] have formulated statistical tests for the detection of gross errors in the reduced set of balances, either collectively (Chi-square test) or individually (normal distribution test). Many statistical tests have been developed and presented such as; the global test by Ripps [2], Almasy *et al.* [19] and Madron *et al.* [20], the nodal test by Reilly and Carpani [3] and Mah *et al.* [8] , the measurement test by Mah and Tamhane [7], and the generalised likelihood ratio (GLR) test by Narisman *et al.* [21]. These published work presented the application of these gross error detection techniques on process simulations. However, the application of a statistical test or a combination of several statistic tests to detect the presence of gross errors in an operating Kraft plant data has not been published.

The object of this paper is to present the application of data reconciliation and a new gross error detection strategy combining four statistical tests, especially developed to be applied to operating Canadian Kraft mills. A brief description of the process under consideration is first presented; it is followed by the techniques that have been used. Finally the reconciliation of measurements is discussed. Some basic properties used in statistic are presented in the appendix.

3.5 Process description

The study is based on an operating Eastern Canadian pulp mill manufacturing newsprint [5] [22] paper using a mixture of ground pulp (60%) and Kraft pulp (40%) from softwood biomass. Only the Kraft pulping plant of the mill was considered in this study. Due to the large variations in instrumentation level of the various sections of the plant linked to their construction period, the measurements of the mechanical pulping plant, necessary for data reconciliation, were lacking.

The Kraft process is the prevalent pulping process in North America [23] by which wood chips are transformed into pulp. The Kraft process is an energy intensive process and a large consumer of chemicals [24]. It is composed of two main lines: the fiber line and the chemical recovery loop. A simplified diagram of the Kraft process is shown in figure 3-1.

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[5] Newsprint is a type of paper weighting between $40 g/m^2$ and $57 g/m^2$ and generally used for publication of newspapers.

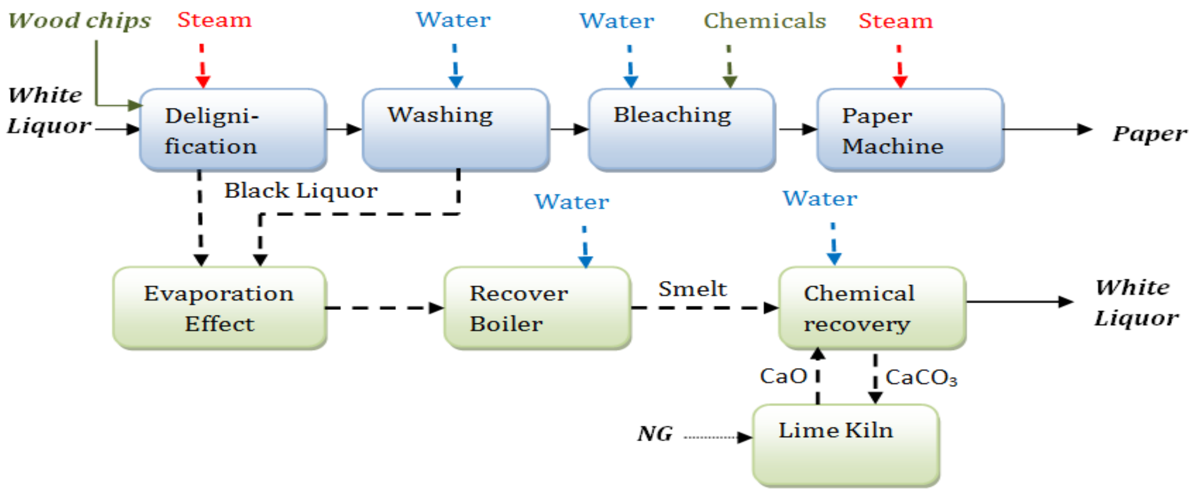

Figure 3-1: Simplified diagram of the Kraft process

The main purpose of the fiber line is to remove the lignin from the fibers in order to produce a pulp of desired quality and specifications. The lignin is removed in 3 steps: digesting, washing and bleaching. The lignin is solubilised by the action of a mixture of sodium hydroxide (NaOH) and sodium hydro-sulfide (NaSH) constituting the white liquor, in the delignification step, and the remaining lignin is removed in the washing step by water, and in the bleaching step by the successive action of oxygen, chlorine dioxide, peroxide and sodium hydroxide. Chemical additives are then added to the bleached pulp to form the paper. Paper sheet is finally drained, pressed and thermally dried in the paper machine.

The cooking liquor separated from the fibers in the washing step is first concentrated in multi-effect evaporators and then burnt in the recovery boiler to produce steam for the mill and to recover the spent chemicals as smelt. The smelt is sent to the chemical recovery department where the white liquor is regenerated. A well managed Kraft process is intended to be chemically and energetically independent.

3.6 Methodology

Plant data have been extracted from PI Processbook ®[6], the data acquisition system of the mill for the year 2013 (winter and summer conditions). A seven step systematic procedure for data reconciliation and gross error detection strategy has been formulated and applied to the operating Kraft mill. The methodology is schematically displayed in figure 3-2 and the successive steps of the methodology are described below. The equation solver software used for data reconciliation and gross error detection computations is MATLAB.

[6] PI Processbook is a computerized software and data acquisition system, to collect, store, manage and monitor real time industrial data, developed and manufactured by OSIsoft, LLC, Inc.

Step 1: Model description
. Identify the measured variables
. Establish the process constraints
. Draw the control volume for the system to be observable and redundant

↓

Step 2: Data collection
. Selection of a suitable time period
. Extraction of plant data, randomly 3 daily averaged values a month for 12 months
. Separation of the year in two periods: hot and cold weather conditions

↓

Step 3: Variance of measured variables calculation

↓

Step 4: Variable classification
. Variable decomposition through matrix decomposition of the reduced constraints, to classify the variables into redundant, non redundant, observable and unobservable variables.

↓

Step 5: Gross error detection
. Normal law test
. Global test
. Combined procedure test: nodal test and measurement test
. GLR test

↓

Step 6: Data reconciliation
. Adjustment of measured variables
. Estimation of observable measurements

↓

Step 7: Results and process leaks identification
. Variables largely adjusted flagged (over 25% adjustment)

Figure 3-2: Organigram of the data reconciliation methodology

1. Model description

For economic and technical reasons, not all variables in a mill are measured. However, some unmeasured variables can still be estimated from other measurements by means of mass and energy conservation laws.

To perform data reconciliation, the system under investigation has to be observable and redundant. This step requires the identification of measured variables and the establishment of the complete process constraints. Once the constraints are established and the variable measurements are identified, the system boundaries can be defined and drawn so that the reconciliation may be feasible.

The concept of observability and redundancy is of paramount importance for data reconciliation. It determines the variables that can be estimated given a set of measurements and constraints, and ensures that the data reconciliation is feasible. It relies on the classification of process variables into observable and redundant variables. A variable is said to be observable when its value is measured or may be indirectly estimated, otherwise, it is said to be unobservable. If the measurement associated with a given variable is deleted, and if the variable remains observable, then the measurement is said to be redundant.

The most frequent problem occurring when performing data reconciliation of an operating mill is the absence or the lack of suitable measurements needed for a complete mass and energy balance determination. The flow rates of the main process streams are usually measured in pulp and paper mills but there are also material flows which are not measured, thereby causing inaccurate balance determination [25]. Data reconciliation requires a large amount of excess data, i.e. the redundancy, to solve the complete set of modeling equations, and improve the statistical value of the final data set, an instance which is rarely encountered in operating Kraft mills, where scarcity of data (negative redundancy) is generally the case [17].

In the model description step, the global redundancy number for each unit operation is computed, in order to determine which department or sector in the mill is suitable for data reconciliation. The lack of a complete set of measurements prevented the reconciliation of the entire mill. Additional measurement devices are needed for the complete reconciliation of the entire mill. For this reason, the departments considered in this study are: the digesting, the washing and the evaporation. Hence, the unit operations are: the cooking vessel (digester), two heat exchangers (cooking liquor HEX), the evaporation effects (6 effects), a fiber deknotter (to separate the uncooked knots from the cooked pulp in the washing department), and two brown stock washers. A total of 8 unit operations, 36 streams, 15 process constraints and 58 process variables describe the system studied (material flow rates, temperature and pulp consistency). The process constraints are primarily the heat and mass balances around the unit operations selected.

In order to have a positive global redundancy for the described system, a minimum of 43 measurements are required for a complete balance determination. There are 53 measurements for flow rates, temperature and pulp consistency, and 5 observable unmeasured variables, therefore the system is observable and the reconciliation is feasible.

2. Data Collection

Plant data are archived on a daily basis in the PI ProcessBook®. The data collected should cover a range of operating conditions (e.g. winter and summer) in order to represent the main process variations. The data for the 53 measurements describing the system have been collected over a period of one year, at random intervals, 3 times a month. Thus, 36 values are collected for each measurement. The collected data are then sorted by season (hot and cold), and averaged.

3. Variance of measured variables computation

The variance calculation for measurements and measurement errors is an important step for data reconciliation. It is likely that some measurements are more accurate than others depending on the instrument being used and the process environment under which it operates. In order to account for this, data reconciliation is based on the weighted least squares of measurement correction, where the weights are chosen to reflect the accuracy of the respective measurements. Generally, it is assumed that the error variances for all measurements are known and that the weights are chosen to be the inverse of these variances. In published data reconciliation application on industrial processes, more accurate measurements are given larger weights in order to force their adjustments to be as small as possible. More accurate measurements are chosen based on the expertise of mill engineers and their experience of the process and are given accuracy percentage ranging from 5 to 25% depending on how much the device is trustworthy [40]. Unlike previous studies, in this step, variances of measurement errors are calculated (and not estimated) based on real time-redundancy of measurements. The variances of measurements are used as basis for computation of measurement errors variances. The same accuracy percentage is given to each measurement. This way, the system is not forced to adjust some measurement more than others, it will iterate until convergence and the resulting adjustments will not be guided by the user.

4. Variable classification

To solve the data reconciliation problem, the variables must be first classified into redundant, non-redundant and observable [5]. The data reconciliation adjusts only the redundant variables. The non-redundant variables are not adjusted, and the observable variables are estimated. Several strategies have been formulated for performing process variable classification. These strategies can be divided into 2 major categories. One category of researchers applies the concept of graph theory to achieve the classification, and the other makes use of matrix ordering techniques and computations [26]. Graph oriented techniques developed by Valveck [5, 6], Mah and co-workers [7, 8], Meyer *et al.* [28] and Kretsovalis [29, 30] require an extensive analysis of the process diagrams, P&IDs (Process & Instrumentation Diagrams) and other derived flow sheets. The application of the graph theory to an operating mill is complicated and not automated. Equations-oriented approaches were developed mainly by Romagnoli and Stephanopoulos [9], Crowe [15], Joris and Kalitventzeff [31] and Madron *et al.* [20, 32]. They are based on the manipulation of the incidence matrix, which corresponds to the Jacobian of process constraints.

Romagnoli and Stephanopoulos [9, 26] proposed a classification procedure based on the application of an output set assignment algorithm to the occurrence submatrix of unmeasured variables associated with linear or nonlinear model equations. Joris and Kalitventzeff [31] developed a procedure for the classification of variables that is accomplished by permuting rows and columns of the occurrence matrix. However, this mathematical procedure fails in the detection of observable variables. Madron *et al.* [20, 32] proposed a classification procedure based on the conversion into the canonical form of the matrix associated with a plant model constituted of linear or linearized equations. The procedure is extensively described in the monograph by Madron *et al.* [20, 32]. Crowe [15] proposed the utilization of the projection matrix P to eliminate the non-measured variables for linear systems. He later extended the method for bilinear systems. In the case of linear and non linear systems, QR factorization introduced by Crowe allows variable classification. QR factorization is the method chosen and applied for the current study because of the simplicity of its application to a system with large data and its suitability to solve bilinear systems. Systems involving heat balances are bilinear. Therefore, Crowe's method is best suited for the system investigated herein.

Moreover, this variable classification step provides insights into where additional measurement devices should be placed in order to increase the global redundancy around unit operations, and helps mill engineers plan the placement of new instruments. In a mathematical way, the covariance matrix of the adjustments (in the reconciliation step) is used to predict optimal places for the addition of new instruments. Iteratively, the covariance matrix is analysed for the addition or removal of a new instrument to the original system. A good criterion for the placement of new measurement is the reduction on the trace of the covariance matrix (the trace of a matrix is the sum of its eigenvalues) as proposed by Kretsovalis and Mah [30]. The measurement whose addition reduces significantly the trace of the covariance matrix is selected. From a graphical method, the addition of new instruments in streams connecting unit operations is recommended. These new measurements increase the global redundancy as they are adjusted from both parts of the neighbouring unit operations. The addition of such measurement will most likely improve the data reconciliation accuracy.

5. Gross Error Handling

It is assumed that measurement errors are normally distributed with zero mean and known covariance. In practice, the process data may contain gross errors caused by non-random events such as calibration errors and equipment malfunctions. The presence of these errors alters the statistical basis of data reconciliation using least squares minimization and causes the measurements to be largely adjusted by error smearing effect [1]. For a successful application of data reconciliation, the gross errors should be identified and the measurements corrected before further processing. The novel approach proposed for the treatment of gross errors in the data reconciliation methodology developed as part of this work is presented in figure 3-3, and described below.

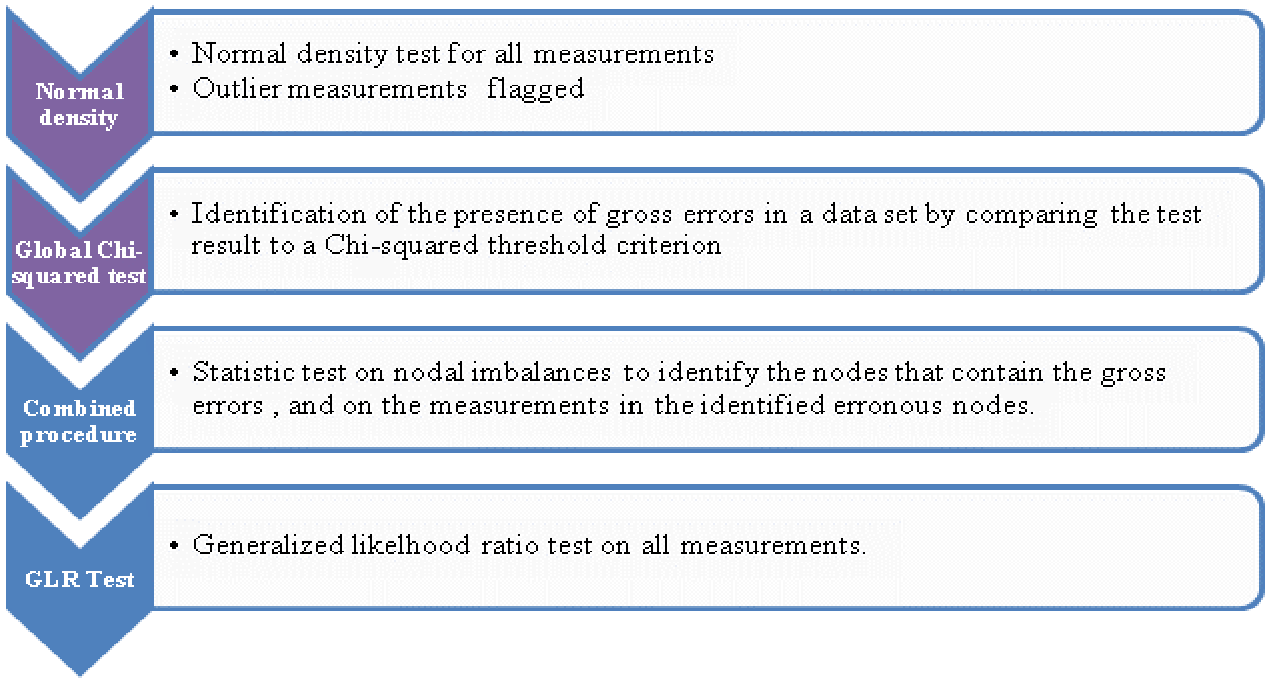

Figure 3-3: Gross error handling strategy

5.1. Detection of gross error

The detection of gross errors in this study is performed by means of two tests: the normal density test and the global chi-squared test, in order to detect the presence of gross errors in redundant as well as in non redundant measurements.

The basic principle in gross error detection is derived from the outlier in statistical applications. The random error inherently present in any measurement is assumed to follow the normal distribution. Thus, the normalized error ($(y-\mu)/\sigma$) also follows the normal distribution. Therefore, most normalized errors should fall inside a ($1-\alpha$) confidence interval at a chosen α. Any value of the normalized error which falls outside the confidence region is declared an outlier or a gross error. Most statistical tests are based on the discrepancies observed in the constraints, and apply only to the redundant variables. The measured non redundant variables may contain gross errors without ever being identified. Thus, an undetected gross error present in a non redundant measurement could contaminate the data set by smearing effect and invalidate the reconciliation results. To avoid this problem, in the present study, all measured variables are screened using the normal distribution. The probability density test is the preliminary step in the gross error detection strategy proposed. It identifies the variables having the largest variances and the outliers could be flagged for further investigations.

Once the screening test is performed by means of normal density distribution, the presence of errors is further verified by the global chi-squared statistic test developed by Mah [1], and constructed from the observed discrepancies in the constraints (referred to as nodal imbalances), namely the matrix r. The test can be written as follows:

$$\gamma = r^T V^{-1} r \tag{1}$$

with r, the vector of the residuals of the constraints, and V, the covariance matrix, such as:

$$r = A\, y \tag{2}$$

$$V = A\, W A^T \tag{3}$$

The matrix W is the error covariance matrix. If all the errors follow the standard normal distribution, then γ will have a chi-squared (χ^2) distribution with ϑ degrees of freedom, where ϑ equals the rank of matrix A (number of degree of freedom equals to the number of balance equations). The computed value of γ (result of the test) is compared against a critical value (a threshold) $\chi^2_{1-\alpha,\, \upsilon}$ obtained from the table of χ^2 distribution. If the result of the global test exceeds the test criterion, then it could be concluded with more than (1-α) % certainty that a gross error is present in the data set, given the confidence level chosen α. In the current study, the level of confidence chosen is 5%.

5.2 Identification of gross error

If the presence of gross error is detected, it is necessary to identify, locate and eliminate the gross error before the reconciliation. The identification of gross errors is performed using the combined procedure and the generalized likelihood ratio (GLR) test.

The combined procedure is a combination of two gross error detection statistical tests performed in sequence; first on the constraints residuals, called the nodal test, and then on the measurements, called the measurement test. The combined procedure is based on the assumption that, if a gross error is present in any flow measurement, then it affects the constraint residual (r) in which the measurement occurs. Hence, the detection and identification of gross errors should be performed on the constraints residual and then on the measurements, in sequence.

Reilly and Carpani [3] and Mah *et al.* [8] independently developed and proposed a statistical test on each nodal imbalance (r). The test is given by equation 4,

$$\gamma = z_{r,i} = \frac{|r_i|}{\sqrt{V_{i,i}}} \tag{4}$$

where r_i, is the vector of residuals of constraint i, and V_{ii} is the corresponding covariance value in the diagonal of V. The value of $z_{(r,i)}$ is compared against a critical value $Z_{1-\alpha/2}$ determined from a standard normal distribution table (or Chi-square table). If the value of $z_{(r,i)}$ exceeds the test criterion; then at least one gross error is present in the constraint r,i.

To locate the gross error in the process constraint identified, Mah and Tamhane [7] proposed the use of a statistical test based on the adjustment made on the measurement in the reconciliation step. The test can be written as follows:

$$\gamma = z_{a,j} = \frac{|a_j|}{\sqrt{W_{j,j}}} \tag{5}$$

In this equation, a, is the adjustment and j, is the number of constraints in the reduced data reconciliation problem. The value $z_{(a,j)}$ is computed and tested for normal distribution. Similarly to the constraint test, the measurement whose removal reduces greatly the results of the test is suspected of containing a gross error.

One limitation of this measurement test is that it assumes one error at a time and therefore it ascribes the probability of presence of an error entirely to one measurement, whereas more than one error could be simultaneously present in the constraint. Therefore, this procedure may amplify the magnitude of the error. One difficulty of its application to a real process is that it requires the removal of the measurement to perform the test. In real operating processes, the removal of one measurement sometimes makes the system unsuitable for reconciliation.

To avoid the error amplification problem, the gross error handling strategy proposed in this study utilizes an additional statistical test, the generalized likelihood ratio (GLR) test. The generalized likelihood ratio (GLR) test is performed on the entire data sample. Unlike other tests, GLR test can be enlarged to identify the presence of multiple errors assuming that the variables are independent. Narisman and Mah [21] proposed the use of GLR test for gross error detection. GLR is based on the maximum likelihood ratio principle used in statistics. It is the ratio of the probability of occurrence of a gross error over the probability of its absence, and is written as follows:

$$\gamma = sup \frac{\Pr\,(f(y)|H_1)}{\Pr\,(f(y)|H_0)} \tag{6}$$

In this equation, H_1 and H_0 are respectively the hypothesis of the presence and absence of a gross error in the measurement tested, and f(y) is the normal density function of the measurement x. Here sup is the calculation of the supremum over all possible values of the parameters in the hypothesis. The test (equation 6) can be simplified, as follows [33]:

$$\gamma = \left\{ \frac{1}{1 + (\frac{1}{\mathrm{n} - 1})(\frac{\bar{\mathrm{y}} - \mu_0}{\mathrm{s}^2/\mathrm{n}})^2} \right\}^n \tag{7}$$

The parameter n, is the number of samples in the measurement, $\bar{y}$ is the average value of the sample, μ_0 is the true mean, and s^2 is the sample standard deviation [34].

6. Data reconciliation

At this step, it is assumed that no gross error remains. Data reconciliation, improves the accuracy of process data by adjusting the process measurements to obtain values that satisfy the system constraints. Since not all process variables are measured due to economic reasons or technical limitations, the redundant measured variables are first adjusted and then the observable unmeasured variables are estimated as part of the reconciliation problem.

The measurement vector (y) can be written as:

$$y = x + \varepsilon \tag{8}$$

Where x, is the vector of true values of the variables and, ε is the vector of random measurement errors, that are normally distributed with zero mean and possess a covariance matrix V as computed in step 3. The data reconciliation can be formulated by the following constrained weighted least-squares optimization problem [35];

$$\min_{x_i, u_j} \sum_{i=1}^{n} [\frac{y_i - x_i}{\sigma_i}]^2 \tag{9}$$

subject to the constraints;

$$g_m \left(x_i , u_j\right) = 0 \tag{10}$$

with m, the number of process constraints, x_i, the measured redundant variables, and u_j the observable unmeasured variables as classified in step 4. The constraints arise because of mass balances, energy balances and any other performance equations that must be satisfied. Several methods presented in the literature have been developed to solve the optimization problem. The complexity of the techniques depends strongly on the constraints imposed. The constraints are linear if they represent global mass balances, and non linear if they represent heat balances. The latter can be linearized and solved analytically. The objective function (equation 9) can then be represented by:

$$\min_{\mathrm{x}} \ (\mathrm{y} - \mathrm{x})^{\mathrm{T}} \ \ \mathrm{V}^{-1} \ (\mathrm{y} - \mathrm{x}) \tag{11}$$

The analytical solution of this optimization problem under linear constraints, with all variables being measures, is obtained by means of Lagrangian multipliers [36, 37], and is given by:

$$\hat{x} = \mathrm{y} - \mathrm{V} \ \mathrm{A}^{\mathrm{T}} (\mathrm{A} \ \mathrm{V} \ \mathrm{A}^{\mathrm{T}} \ )^{-1} \ \ \mathrm{A} \ \mathrm{y} \tag{12}$$

The constraints are:

$$\mathrm{Ax} = 0 \tag{13}$$

The incidence matrix is A, and V is the covariance matrix of random errors. If the constraints are nonlinear (the case of heat balances for instance), then they must be linearized. Several linearization methods are possible. The successive linearization is one of the most popular methods for data reconciliation applications [38]. The general principle of the successive linearization technique is to linearize the constraints using a Taylor expansion to the first order around the estimated values of the variables, and to iterate until an optimal point is obtained satisfying the non-linear constraints [3]. Successive linearization using Taylor's expansion is the method recommended for bilinear systems [7] at steady state [38], and is used in the present study [39].

When the data set contains unmeasured variables, the solution can be obtained by the method of orthogonal QR factorization developed by Crowe (the method also applied in step 4 of the methodology for variable classification). The incidence matrix (A) can be divided into two matrices: one which contains the measured variables (A_x), and another which contains the non-measured ones (A_u) [36]. The constraints will then be expressed as:

$$A_x\, x + A_u\, u = 0 \tag{14}$$

Unmeasured variables are first removed by multiplying both sides of the equation (14) by a projection matrix, P, so that [3]:

$$P\, A_u = 0 \tag{15}$$

The reconciliation problem becomes [36]:

$$\min_{x,u}\ (y - x)^T\ \ V^{-1}\, (y - x) \tag{16}$$

Under the constraints,

$$P\, A_x\, x\ = 0 \tag{17}$$

The projection matrix P is obtained by applying the method of QR factorization of the matrix A_u. The details of QR factorization and the projection matrix P is in the appendix of the article. The solution of the optimization problem is obtained by replacing the matrix A by the matrix PA_x, in the equation 12 [36]:

[7] Bilinear systems are a special case of non linear systems, in which non linear terms are constructed by multiplication of control vector and state vector such as: $y^T A_x$ = constant.

$$\hat{x} = y - V\,(P\,A_x)^T (P\,A_x\,V\,(P\,A_x)^T\,)^{-1}\,(\,P\,A_x\,)y \tag{18}$$

Once the measured variables are reconciled, the unmeasured variables can be estimated using the following equation:

$$\hat{u} = -(A_u^T A_u)^{-1}\,(A_x\;\hat{x}) \tag{19}$$

7. Results and process leaks identification

Once the redundant measurements are reconciled and the observable variables estimated, the variables which have been the object of large adjustment (±25% of adjustment) are flagged for investigation. Those strongly adjusted variables could be symptomatic of process leak or inefficient unit operation.

3.7 Results and discussions

The methodology for data reconciliation and gross error detection was applied to a set of 53 measurements describing the Kraft process. Table 3-1 summarizes the characteristics of the model studied. As mentioned in the methodology, the model considered and described in table 3-1 does not include the bleaching and the recausticizing department of the Kraft pulping process because the global redundancies in these departments were negative which made the reconciliation impossible.

Table 3-1 : Model description

Departments	Unit operations	Process constraints	Type of measured variables	Nb. of streams	Nb. of variables
Digesting	1 Cooking vessel	Global mass and heat balances	Mass flow rates and temperature of streams	10	22
	2 Black liquor heat exchangers			6	
Washing	1 Blow Tank	Global and partial mass balances	Mass flow rates and pulp consistency	5	26
	1 Deknotter			4	
	2 Brownstock washers #1 and #2			13	
Evaporation	6 Effect evaporators	Global mass and heat balances	Mass flow rates and temperature of stream	5	5

Values for mass flows rates, temperature and consistency of the 43 streams was collected for a period of one year, randomly three times a month (three daily average measurements). A total of 36 values for each of the 53 measurements were collected, averaged and separated into 2 groups, for summer and winter Canadian weather conditions. Variances for measurement and measurement errors were computed and variance, covariance, and the incidence matrices were constructed. The incidence matrix represents the Jacobians of the process constraints and serves for variable classification computation by Crowe method for QR factorization.

The results of variable classification performed at step 4 of the methodology, and displayed in figure 3-4, provide a good visualization of the places of the redundant, non redundant and observable variables in the mill. From figure 3-4, one can notice that when there is an unmeasured variable around a unit operation, it is very likely that there is one or more non-redundant measurement around the same unit operation.

For the case study, 15 % of the measured variables are non-redundant, and therefore not taken into account in the reconciliation problem, and in the combined procedure for gross error detection. The increase of global redundancy through the installation of new measurement instruments would improve the accuracy of the reconciliation results.

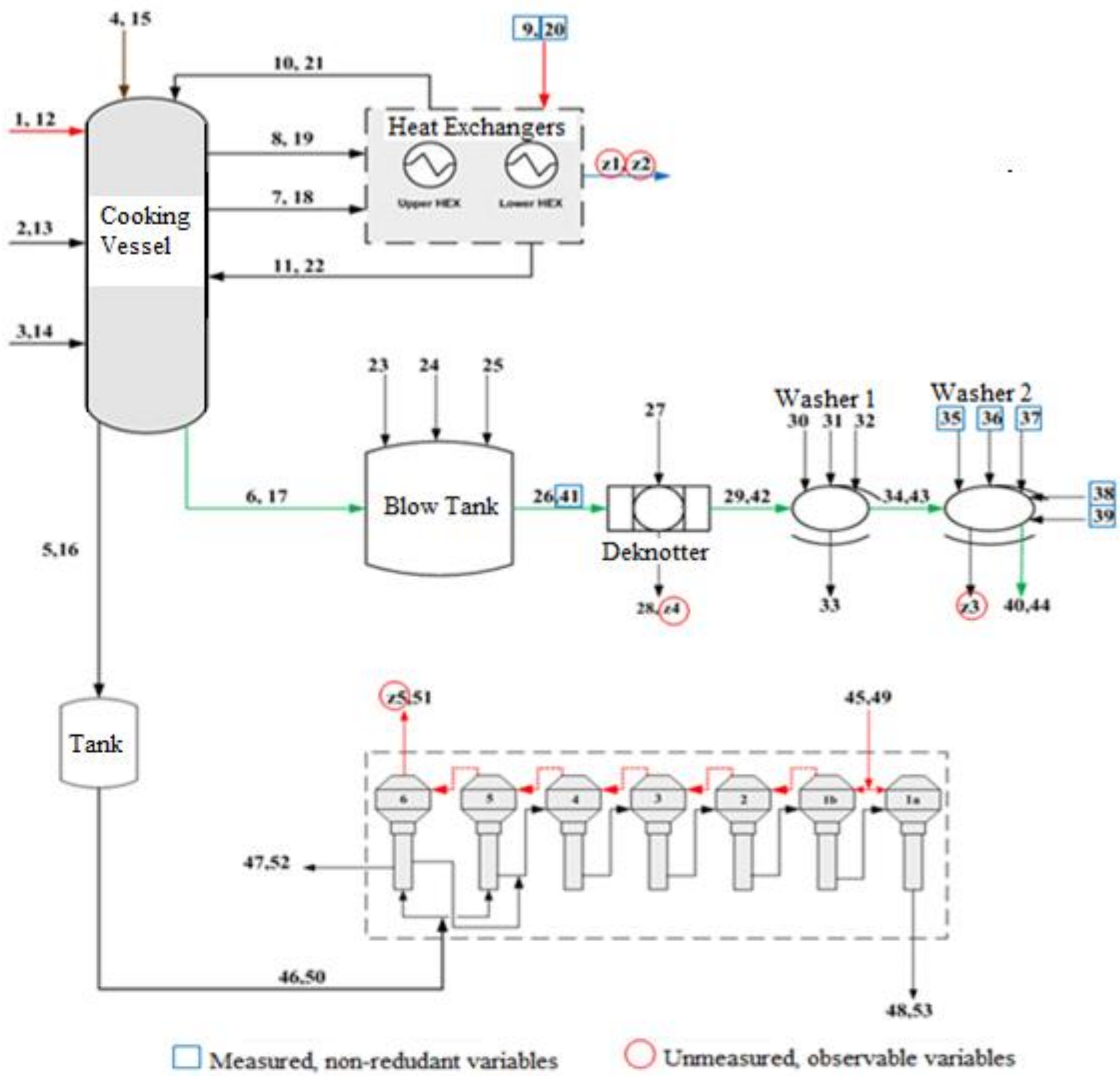

Figure 3-4: Variable classification

Most published strategies for gross error detection in industrial processes are applied to redundant variables only. The strategy proposed in this work is based on the use of 4 statistical tests to ensure that gross errors are detected not only on redundant variables, but also on all process measurements (redundant and non redundant). The global test yielded values higher than the threshold for the washing and the evaporation departments, which suggested with better than

99.5% certainty, that at least one gross error is present in each department as indicated in table 3-2.

Table 3-2 : Results of the global test

Sub-system	α	Degree of freedom	γ Calculated	Threshold	Conclusion
Cooking Vessel	0.1	2	1.7	4.6	H_0 accepted
HEX	0.1	1	0.7	2.7	H_0 accepted
Washing	0.1	5	247.8	9.2	H_0 rejected
Evaporators	0.1	1	9.10E+05	2.7	H_0 rejected

The normal distribution screening test for all 53 process measurements suggested that 7 measurements may contain a gross error (y31, y35, y36, y43, y46, y51 and y53). Two of these measurements (y35 and y36) are non-redundant and do not participate in the reduced reconciliation problem. However, this screening is further evidence of the presence of gross errors in the washing and evaporation areas. The normal distribution test confirmed the global test results, and the measurements suspected of containing gross errors are collected from unit operations in the washing and the evaporation. The measurements y31, y35, y36, y43 are entering, leaving or connecting washers #1 and #2, and the measurements y51, y53 and y46 are entering and leaving the evaporation department. It could not be detected by the combined procedure or by other gross error detection techniques available in the literature that measurements y35 and y36, actually contain gross errors.

In the combined procedure, the measurements whose removal results in the largest reduction in $\chi 2$ test results are suspected of containing a gross error. The results of this procedure, shown in figure 3-5, suggested the presence of one or more gross errors in the washing department. They involve the measurements y30, y31, y32 and y33 collected on washer #1.

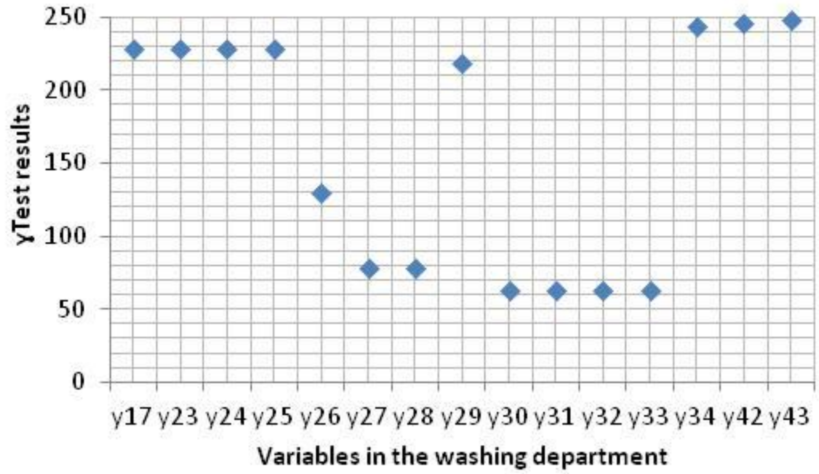

Figure 3-5: The results of the gross error detection by the combined procedure for the measurements in the washing department

Finally, the generalized likelihood ratio (GLR) test, performed on the entire data set rather than only redundant variables, suggested the presence of gross errors in the measurements y35, y36, y37, y38 and y39. These measurements were taken on washer #2. All five measurements represent wash water flows entering this washer. Measurements y35 and y36 (non-redundant) are incriminated by both the GLR and the normal distribution tests. The detection of these gross errors raises interrogations considering the water consumption and the performance efficiency of the washing department.

In spite of the disagreement in the identification of faulty measurements, the results of the four statistical tests performed for gross error detection are not in contradiction. They all identified measurements in the same area (the washing department), taken at connecting washers (washers 1 and 2). In fact, the statistical tests used are complementary since two are based on redundant variables only, and the other two are based on the entire data set.

Figure 3-6 summarizes the results of all gross error detection techniques applied. All detection techniques point to variable y31 as suspected of containing a gross error. Because of the smearing effect, the error may be causing other measurements to be falsely identified. The magnitude of the error has been estimated and the measurements corrected and reintroduced into the system for further data reconciliation.

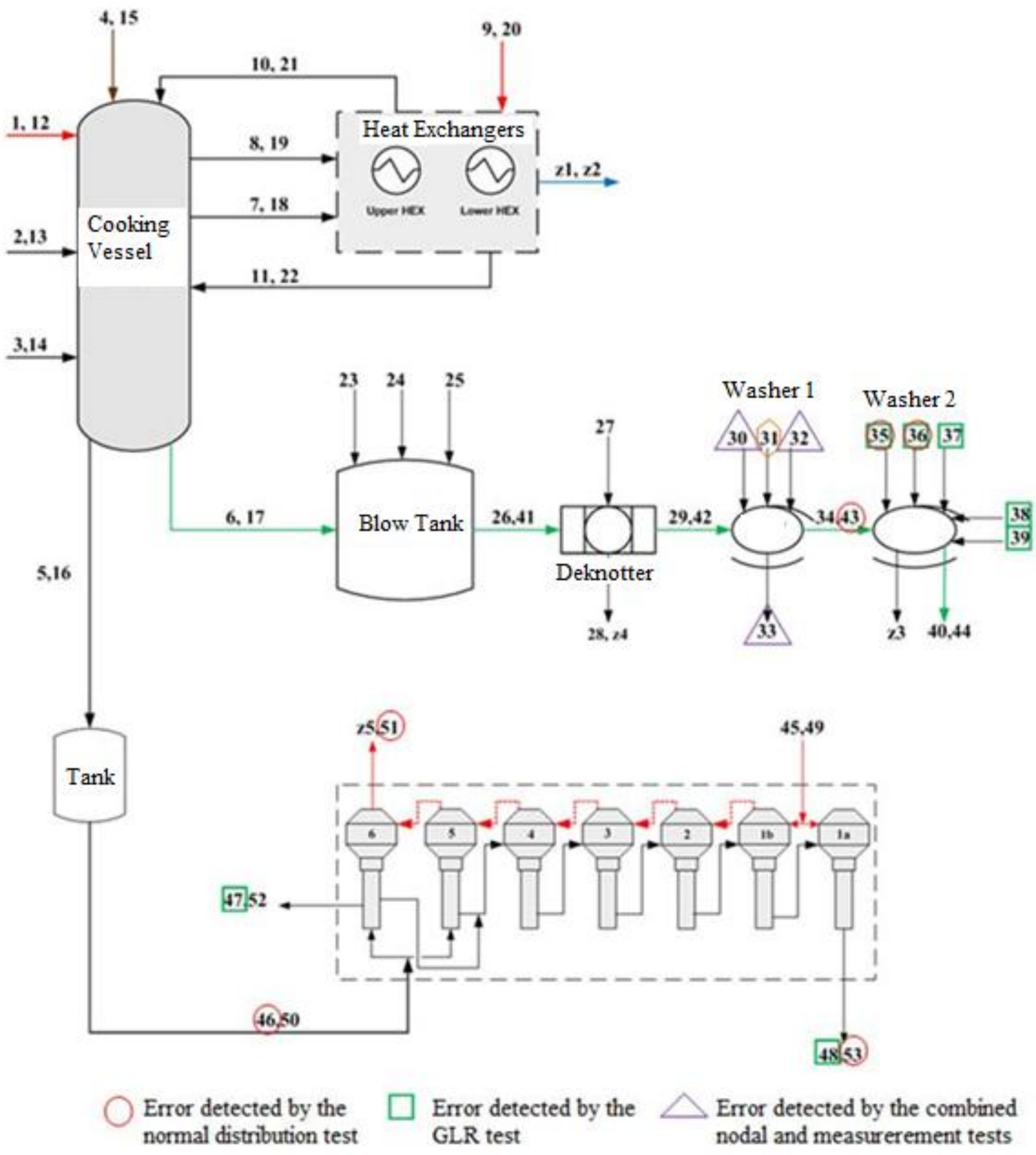

Figure 3-6: Variables suspected of containing gross errors, detected by the different gross error detection techniques applied

To increase the precision of the results, data reconciliation constituting step 6 of the methodology was performed on each unit operation and extended to include the neighbouring operations. Therefore, two reconciliations are performed to exploit the maximum redundancy of the measurements and the process constraints.

Figures 3-7 and 3-8 identify the variables of the mill that are strongly adjusted by the reconciliation. The results show that the areas suspected of containing gross errors are also where the variables have been strongly adjusted. These results point to poor efficiency of unit operations, process leaks or even equipment failures.

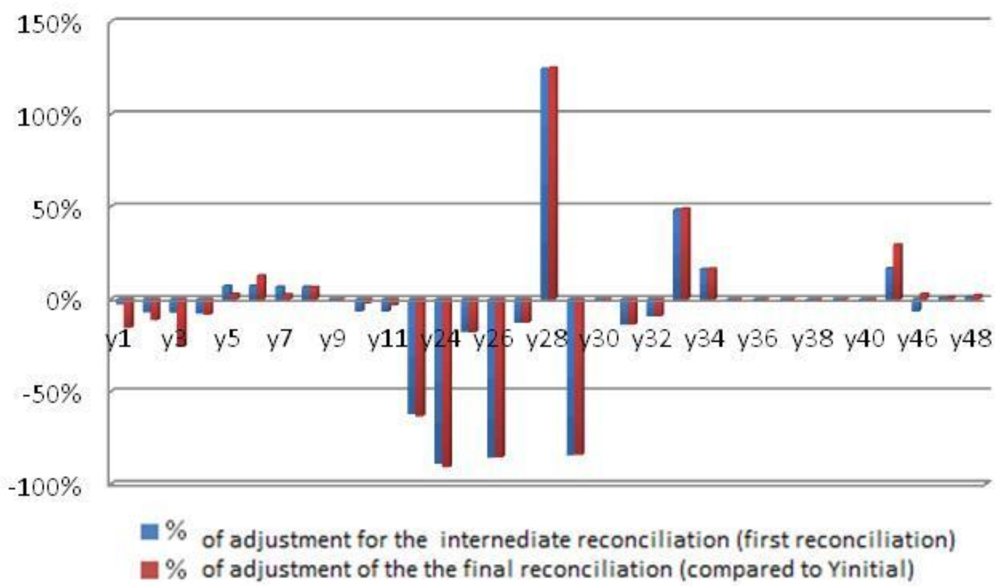

Figure 3-7: Results of the reconciliation of the mass flow measurements - (%) adjustment

The two brown stock washers are the unit operations containing the variables that are strongly adjusted. Since the variables are connected through physical balance constraints, the strongly adjusted variables are both entering and exiting the unit operations, aggregated around these specific units. Therefore, it can be surmised that the washers are over consuming water because of poor performance. These results are actually congruent with the gross error detection results. The mill analysed effectively consumes large amount of water, probably due to faulty operating conditions in the washing equipment. It should be possible to reduce its overall water consumption.

Further diagnostics using additional and specific performance indicators should be combined to this study to complete the evaluation, in order to determine the optimum water consumption.

The results of the reconciliation for temperature variables (figure 3-8), on the other hand, indicate that they have not been strongly adjusted. This is usually the case in pulp mills where steam and energy consumption are closely controlled and monitored, because they are in direct relation with the operating cost and the economic profitability of the mill.

Figure 3-9 graphically synthesises the results of the data reconciliation methodology. The strongly adjusted areas in the mill are highlighted. The wash shower flow rates of washers #1 and #2 should be monitored closely by mill personnel. These two equipments show signs of poor performance and further investigation is needed on these unit operations. The results of this methodology have been validated with mill personnel and who agreed with the results.

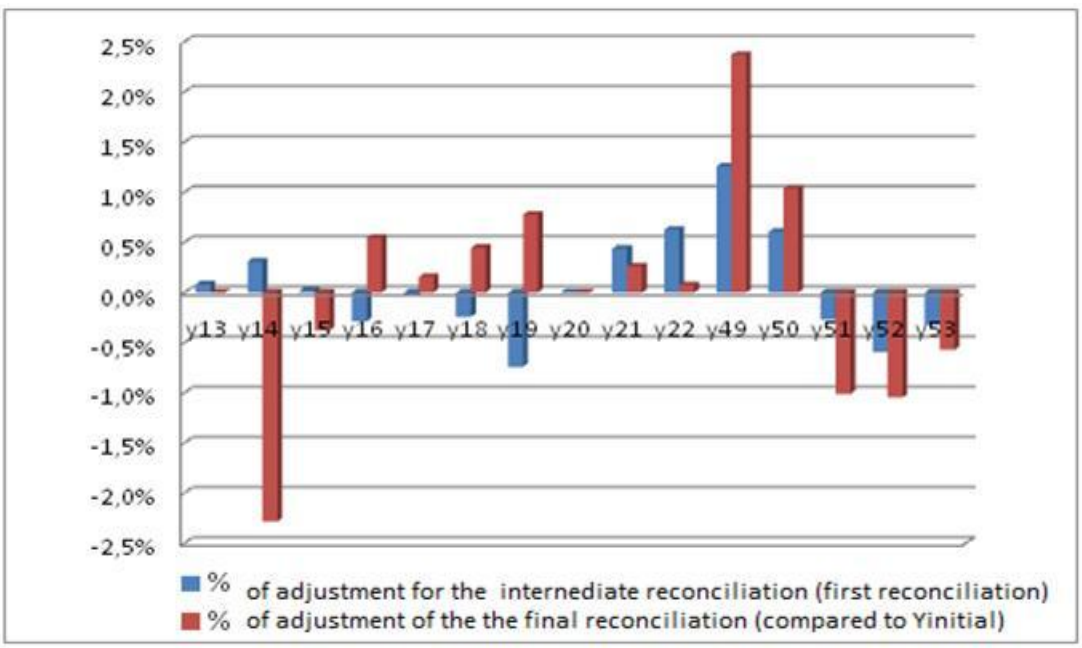

Figure 3-8: Results of the reconciliation of the temperature measurements- (%) adjustment

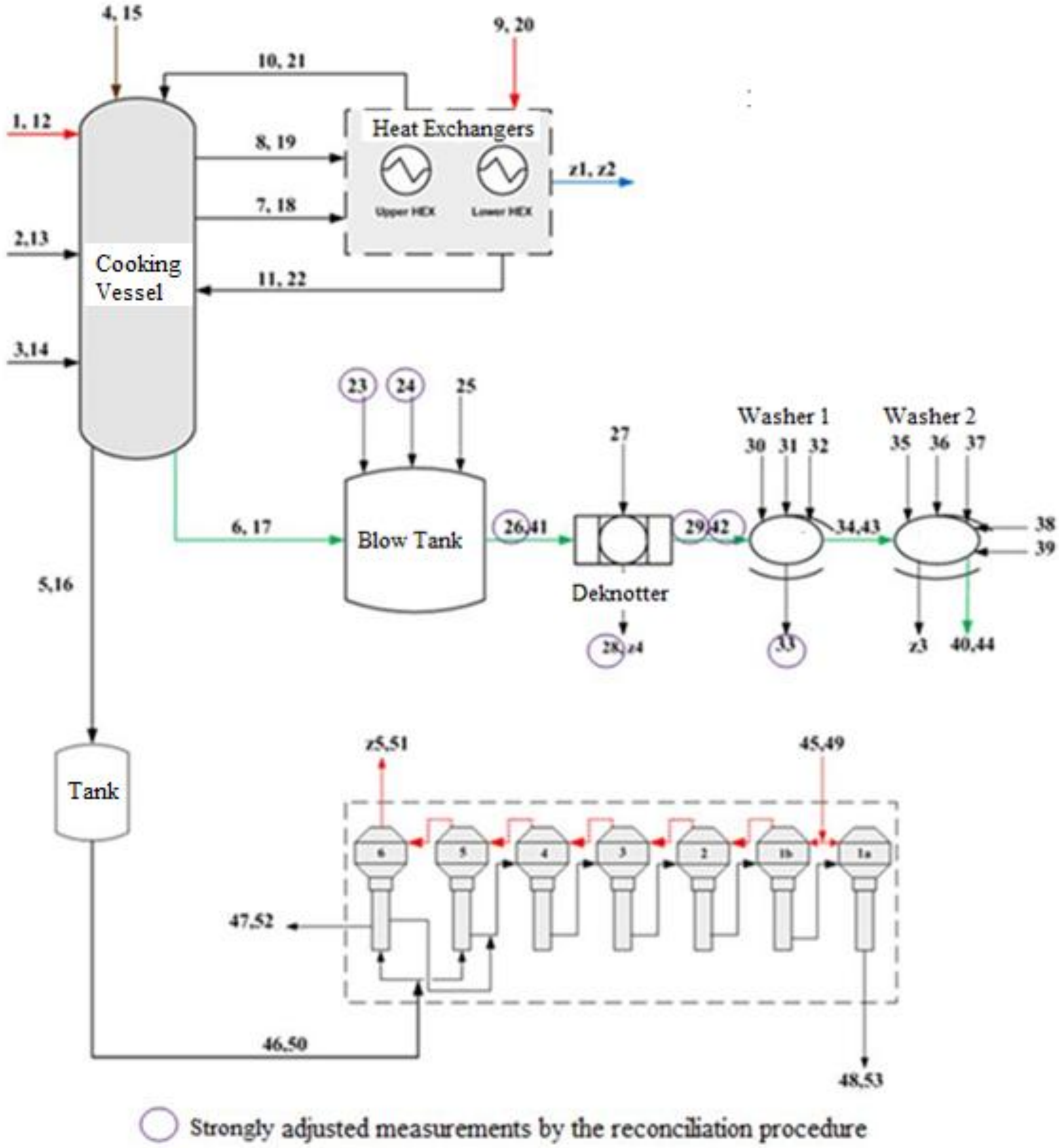

Figure 3-9: Variables strongly adjusted by the reconciliation

3.8 Conclusion

Steady-state reconciliation and gross error detection is a mature field but remaining challenges are hindering its application to Kraft pulp processes. Gross error detection and sensor location is an emerging field, for which efficient techniques that address practical issues are still in development. In some cases, data reconciliation is not feasible due to lack of measured variables.

Generally, Kraft mills need to place additional measurement devices to increase data reconciliation feasibility and precision.

This case study shows that the strategy used for the analysis of a Kraft plant by means of data reconciliation possesses good ability to identify, to locate gross errors, and to correct process measurement. Data reconciliation generates a congruent set of data that represents a long term average of the theoretical steady state of the mill, and identifies unit operations with poor efficiency. It is therefore an important adjunct to advanced control and optimisation.

The proposed strategy for gross error handling gave satisfactory results and efficiently located and identified the gross errors in the mill. It is highly recommended to combine more than one gross error detection technique when dealing with real operating processes and to screen all raw measurements, rather than the reduced redundant data set in order to avoid the error smearing effect.

The results of the study show that the gross error detection techniques identified gross errors in the washing and evaporation departments. The reconciliation results showed strongly adjusted variables in the washing area around the two washers. The water consumption of these washers should be monitored and could be reduced. Potential savings could be generated in the washing department at low investment costs. The washing department is an intense water consumer. Reducing water consumption will reduce the energy consumption of the plant and related operating cost.

To increase redundancy and accuracy of data reconciliation results, new instruments should be strategically implemented. It is in particular recommended to place new instruments to monitor water leaving the washer #2. Graphical method and covariance matrix analyses are useful tools to identify optimal placement of new instruments. Additional measurements will create opportunity for deeper and more thorough performance analysis by mill engineers.

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Appendix

1. Basic properties used in statistics

The mean value μ, the standard deviation s, and the covariance (cov(y)), are important properties for statistical calculations. The mean value μ_y, for the variable y, is calculated by [38]:

$$\mu_y = \frac{\sum_{n=1}^{N} y_i}{n} \tag{20}$$

In which, N is the number of samples and the index y indicates the measurement. The mean value is used to compute the standard deviation, where the standard deviation is:

$$s_y = \sqrt{\frac{\sum_{n=1}^{N} (y_i - \mu_y)^2}{n-1}} \tag{21}$$

s_y which is equal to the square root of the variance. The covariance can be computed by equation 22:

$$cov(y) = \frac{\sum_{n=1}^{N} (y_i - \mu_y)}{n-1} \tag{22}$$

and the measurement covariance matrix can be expressed by equation 23:

$$cov(Y) = \frac{1}{N-1} Y^T Y \tag{23}$$

where N, is the number of observations.

In this paper, different statistical hypothesis tests are presented (global test, measurement and nodal tests and GLR tests). To perform a hypothesis test, a null hypothesis H_0, and an alternative hypothesis H_1 are required. For the test chosen, a significance level α is fixed, to determine the uncertainty of the test. If α is 5% then there is 5% chance of rejecting the null hypothesis when it should have been accepted. This is called type I error, or false alarms. A type II error occurs when the alternative hypothesis is rejected although it is true. The tests result in a quantity that is compared to a criterion or a threshold to decide whether or not the null hypothesis is accepted.

2. Crowe's Method for QR factorization

Let A_u be an invertible matrix of dimension ($m \times n$) (using a permuting matrix to permit the inversion of the matrix), with $m \geq n$, and with n linearly independent columns. There exist one unique couple (Q, R) where Q is an orthogonal matrix of dimension ($m \times m$) and R is a superior triangular matrix of dimension ($m \times n$), and all the diagonal coefficients being positive, such as $A_u = QR$, with:

$$Q^T Q = I \qquad \text{and} \qquad R = \begin{bmatrix} R_1 \\ 0 \end{bmatrix} \tag{24}$$

R_1 is an upper triangular matrix of dimension ($n \times n$),

0 is a matrix full of zeros of dimension ($(m\text{-}n) \times n$), and

I is an identity matrix.

The factorisation of A_u could be performed using the following Matlab command:

[Q , R] = qr (A_u).

The matrix Q, obtained after the factorisation of A_u, could be divided by Q_1 of dimension ($m \times n$) and Q_2 de dimension ($m \times m\text{-}n$). A_u could be written as:

$$A_u = [Q_1 \quad Q_2] \begin{bmatrix} R_1 \\ 0 \end{bmatrix} \tag{25}$$

If both sides of the equation are multiplied by Q_2^T , the following equation is obtained:

$$Q_2^T A_u = Q_2^T [Q_1 \quad Q_2] \begin{bmatrix} R_1 \\ 0 \end{bmatrix} \tag{26}$$

With Q an orthogonal matrix:

$$Q_2^T [Q_1 \quad Q_2] \begin{bmatrix} R_1 \\ 0 \end{bmatrix} = [0 \quad I] \begin{bmatrix} R_1 \\ 0 \end{bmatrix} = 0 \tag{27}$$

Consequently :

$$Q_2^T\, A = 0 \tag{28}$$

From equation (28), it can be concluded that the desired projection matrix is Q_2^T :

$$\mathrm{P} = Q_2^T \tag{29}$$

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CHAPTER 4. ARTICLE 2: EXERGY ANALYSIS OF A CANADIAN KRAFT MILL USING NEW PRACTICAL EXERGY CONCEPTS

4.1 Presentation of the article

This paper has been submitted to the Entropy Journal. The application of exergy efficiency as a key performance indicator for unit operations to a real operating Kraft mill is presented. Thermodynamic imperfections and poor performing equipment and unit operations were targeted and causes of inefficiencies were diagnosed. Improvement projects and recommendations were proposed.

4.2 Abstract

This paper presents an exergy analysis conducted on an Eastern Canadian Kraft pulp mill with the aim of evaluating the thermodynamic performance of the process, using new concepts of avoidable exergy losses and inevitable exergy destruction. These concepts are introduced and then used to identify the location, the magnitude and the sources of thermodynamic inefficiencies, and determine the maximum potential savings. The application of these new concepts of exergy analysis leads to the detection of practical possibilities of improvements. The exergy efficiency, exergy destruction and loss ratios are determined for the seven most representative sections of the process and the areas with the largest inefficiencies and the biggest savings potential are identified. The results show that the inevitable exergy destruction ratios are highest in the power plant and the bleaching section. The power plant and the washing department are sources of high avoidable exergy losses because of their large production of stack gas and liquid effluents, respectively. Practical modifications with the biggest savings potential are proposed to improve the overall process thermodynamic efficiency.

Key Words: Kraft, pulp and paper, exergy analysis, energy, performance.

4.3 Introduction

The pulp and paper industry is one the most energy intensive sectors, consuming approximately 30% of the industrial energy in Canada [1, 2]. Energy is a significant production-cost component (about 25 % of total) in pulp and paper manufacturing [1]. With increasing energy prices and intensive competition from emerging economies, the Canadian P&P industry is compelled to continuously examine its existing processes and improve their efficiency in order to remain competitive. As well, the sector reduced its energy use by an average of 1 percent annually since 1990 through improvements in energy efficiency, by the application of energy integration techniques and energy enhancement methodologies [1]. Several process integration techniques such as pinch analysis, exergy analysis and energy optimization have been developed and used independently or in combination for energy integration and performance improvement of pulp and paper processes [3]. Thermodynamic analysis based on both energy and exergy have been of scientific interest for several decades [4]. A number of exergy analyses of industrial and chemical processes such as pulp and paper mills [5], steam power plants [6], power cycles [3], ammonia production [7] as well as chemical reactors [8], have been presented. It has been demonstrated that exergy is an effective tool for evaluating, analysing and improving the performance of processes [9]. Exergy analysis provides information on the maximum savings that can be achieved in a process and identifies the sections or departments where promising improvements can be implemented [10, 11].

Unlike conventional energy analysis that is mainly based on the first law of thermodynamics, exergy relies on the first and the second laws of thermodynamics. It takes into account the properties of the system environment and considers the energy conversion stages in the process where the quality of energy is degraded. This type of analysis gives an accurate insight into the process and its specific components and yields original ideas for improving water, energy, and power use. Exergy analysis also provides a good overview on the resources utilization, management and process emissions; therefore, it can be used for environmental studies [11]. The literature on exergy offers many examples of its applications. Gong *et al.* [10-12] presented an exergy study combined with life cycle analysis (LCA) of a Swedish pulp and paper mill. The combination of exergy and life cycle analysis reveals the environmental impacts of the resource management in the process. To be sustainable, industries need to keep their waste streams below a certain level of acceptance. LCA allows a complete evaluation of resources utilization and emissions of the process throughout its life cycle. In their studies, the largest exergy losses occur in the boilers and the heating processes are highly inefficient. Wall *et al.* [11] also considered the appropriateness of utilization of exergy as ecological indicator for sustainable development. Gemci and Ozturk [13] presented an exergy analysis of a Turkish sulphide preparation process and highlighted the relevant use of exergy over energy in the diagnostic of the causes of inefficiencies in the process. Regulagadda *et al.* [14] presented an energy and exergy analysis of a thermal power plant and showed that the larger losses of exergy occur in the boiler whereas when energy analysis is performed, the condenser is found to be the least efficient element. Their study highlighted the differences between the two concepts. They showed that energy analysis, because it does not consider the entropy generated and the quality of energy, fails to correctly identify the process thermodynamic inefficiencies and to assess its real performance. Sorin *et al.* [15] presented an integration of pinch analysis to thermodynamic analysis of a process through the exergy load distribution method that provides an analytical expression of the relationship of the individual unit operations constituting a process and its overall efficiency . They demonstrated the effectiveness of the proposed method in improving systems by applying it to a unit for the production of hydrogen using methane reforming. Cornelissen *et al.* [16-20] suggested that to determine the optimal design of an energy system, exergy analysis and life cycle analysis should be combined in order to have a sustainable and energy efficient process. Feng *et al.* [3] combined pinch and exergy analyses for improving a combined-cycle power station. They exploited the advantages and strength of both exergy analysis and pinch procedure. Tsatsaronis [21] highlighted the strengths and limitations of published exergy analyses presented in the literature. He concluded, based on the review of those exergy studies that the concept of exergy is often viewed as abstract and its practical application to operating processes complicated. It is agreed that exergy is valuable in identifying the areas of inefficiencies and gives specific insights into process components and zones of exergy destruction, but it does not provide information on how the process could be practically improved.

Unlike previous studies, this new study introduces new concepts of avoidable exergy losses and inevitable exergy losses that help identify practical improvement projects. The application of exergy analysis on a Canadian Kraft pulp mill has not been presented. The objective of the work is to characterize the thermodynamic performance of Kraft process major equipment using a novel approach relying on the concepts of avoidable exergy losses, and inevitable exergy destruction. The application of this approach helps to identify the maximum practical savings achievable and where improvements can be implemented in the process. Practical improvement projects and recommendations for the pulp and paper mill to improve their overall thermodynamic performance are proposed.

4.4 Case Study

The study is based on an operating Eastern Canadian Kraft mill manufacturing publication grade paper (newsprint [22][8]) using a mixture of ground pulp (60%) and Kraft pulp (40%) from softwood biomass. The average pulp production rate of the Kraft mill is 280 adt/d. The core of the Kraft process was built in the 1930's but process upgrades were implemented later, the last major modification being the addition of a paper machine in the 1990's. Due to the large variations in instrumentation level of the various sections of the plant linked to their construction period, only the Kraft pulping plant of the mill was evaluated in the study. A prorated fraction of steam and water consumption by the paper machine was used in the exergy efficiency analysis to account for the extra pulp fed to the paper machine and coming from the mechanical part of the mill. The Kraft process has been simulated on the CADSIM Plus® software (Aurel Systems Inc). CADSIM Plus is a commercially available chemical engineering software that has been widely used in the pulp and paper sector to simulate process models. The process simulation was built with the purpose of obtaining a reliable representation of a long term average steady-state of the mill, as data source for performance evaluations. A high level schematic of the Kraft process is given in figure 4-1.

[8] Newsprint is a type of paper between 40g/m2 and 57g/m2 generally used in the publication of newspapers. The furnish is largely mechanical wood pulp with some chemical wood pulp.

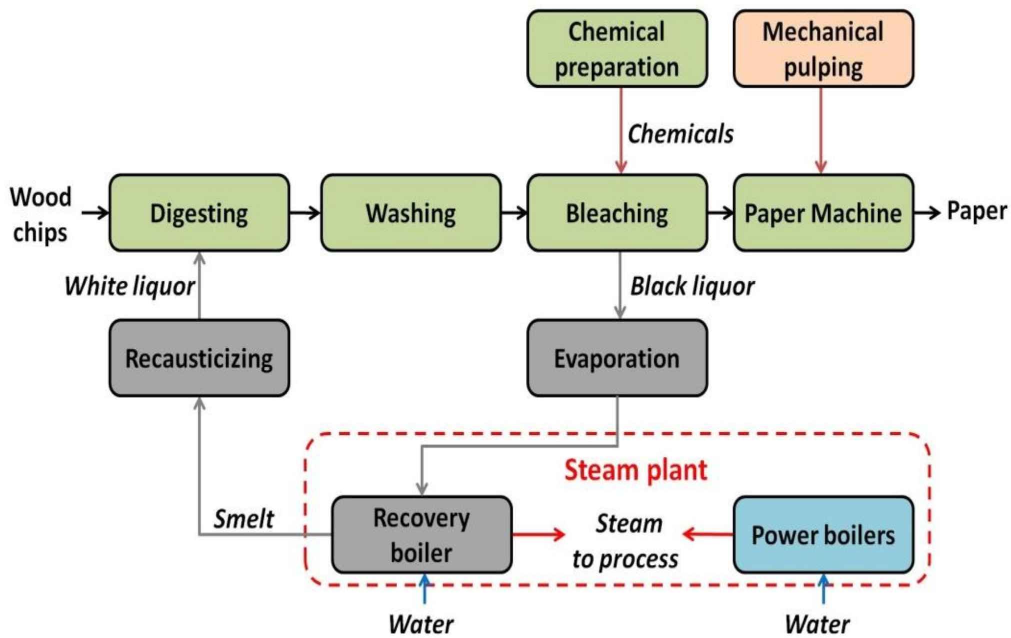

Figure 4-1: Simplified diagram of a Kraft process.

The Kraft process is the worldwide prevalent pulp manufacturing process [23] from which a wide spectrum of finished or semi-fished paper products is made. The core of the Kraft process is the chemical delignification step that takes place in a digester where lignin is separated from the cellulosic fibers. The delignification agent is a solution of sodium hydroxide and sodium sulfide. The pulp produced in the digester is washed through countercurrent washers and then chemically bleached in a series of bleaching sequences at different pH and temperature conditions and using different bleaching chemicals. The bleached pulp is then drained, pressed and thermally dried. The spent delignification liquor separated from the fibers in the washing step (black liquor), is concentrated in the multi-effect evaporators and then burnt in the recovery boiler to produce the steam required for the process and recover the spent chemicals. The spent inorganic chemicals form a smelt that is collected at the bottom of the recovery boiler and is composed mainly of sodium carbonate and sodium sulfide. The smelt is dissolved to form green liquor and then recaustified to regenerate the white liquor which is the delignification liquor. The calcium carbonate (co-product of sodium hydroxide) is burnt in the lime kiln fired with natural gas to regenerate the lime required for recaustification. Several chemicals are used in the bleaching and the recausticizing departments (ClO_2 produced on site, and purchased O_2, H_2O_2 and NaOH).

The Kraft mill consumes about 110 MW of steam, 1400 m^3/h (96 m^3/adt) of water and produces 1760 m^3/h (108 m^3/adt) of effluents (the effluents amount is higher than the water consumption because of the condensation of injected steam). The mill steam requirements are supplied by the recovery boiler and four additional boilers: one is fired with bark and three natural gas (NG) boilers. The digester, the evaporators and the paper machine departments are the largest steam consumers. The washing department is the largest water consumer. It should be noted that a well-managed Kraft mill could be in principle energetically self-sufficient. The utilization of fossil fuel for steam production in the process is a sign of poor energetic performance. Fossil fuel should only be used to absorb the fluctuations of pulp production and seasonal variations of the steam demand (10% higher average on winter conditions in the Canadian context). The assessment of thermodynamic performance of the individual equipment is an appropriate means to determine and plan improvement modifications and the replacement of inefficient equipment.

4.5 Methodology

Exergy: Theoretical Concepts

Energy efficiency analyses are generally based on a comparison between the current process energy consumption and its ultimate consumption obtained by maximization of the internal heat recovery. Energy conversion stages where the quality of energy is inevitably degraded due to entropy generation are ignored by conventional integration techniques such as pinch analysis or mathematical optimization that aim to maximize internal heat recovery, and are based on the first law of thermodynamics. Therefore, these types of energy efficiency analyses can be misleading because they do not consider the quality of energy. For instance, energy losses can represent large quantities but be thermodynamically insignificant because of their low quality (temperature). It is in such situations that exergy analysis becomes relevant, because exergy is a measure of both quality and quantity of energy and it can then be used to quantify the inefficiencies (entropy generation) in a single process or its components if it is applied correctly [24]. Entropy measures the degree of disorder in a system or a process. It is an extensive property that represents the amount of energy in a system that is no longer capable to produce work [24]. The second law of thermodynamics states that the entropy of a real system increases inevitably and it cannot be reduced back to its initial state [25, 26]. Exergy as defined by Szargut [27] is the maximum amount of work that can be produced by bringing a process stream in thermal, mechanical and chemical equilibrium with its environment by a series of reversible operations. However, all real processes are irreversible with the consequence that exergy is destroyed due to entropy generation. Therefore, unlike energy, exergy is not balanced for real processes. For this reason, the exergy and energy efficiencies should be treated and investigated by different ways.

Exergy efficiency concepts have been introduced first by Grassman in the 1950' [28]. He expresses the exergy efficiency as the sum of all the exergy input streams, considered as useful exergy over the sum of all the exergy output streams, also considered as useful exergy as expressed by equation 1.

$$\eta = \frac{\sum \mathrm{Ex}_{\mathrm{out}}}{\sum \mathrm{Ex}_{\mathrm{in}}} \tag{1}$$

For reversible processes with no exergy destruction, this definition always gives 100% efficiency. For real processes, on the other hand, as the thermodynamic efficiency of the process increases, less exergy is destroyed. Ultimate efficiency is achieved only at equilibrium (reversible process), i.e. infinitely slow process which is not a practical engineering option. However, part of the exergy output from the system may be dissipated into the environment as sewered wastes or stack gases emissions. This exergy lost is no longer utilizable by subsequent processes, therefore it is more appropriate from an engineering point of view and from the standpoint of downstream operations to consider the exergy that remains utilizable rather than the total output, and accordingly the definition of the Grassman efficiency is not best suited for real industrial applications. Fratzcher [29] introduced a slightly different exergy efficiency definition, that considers the exergy of output streams of products rather than the total exergy:

$$\eta = \frac{\sum \mathrm{Ex}_{\mathrm{product}}}{\sum \mathrm{Ex}_{\mathrm{in}}} \tag{2}$$

The exergy of a system or a stream is the sum of the contribution of all its forms of exergy; potential, kinetic, thermal, chemical and electrical, and is completely determined by its temperature, pressure and composition in regards to a reference state.

$$\mathrm{Ex_{tot}} = \mathrm{Ex_p} + \mathrm{Ex_k} + \mathrm{Ex_{th}} + \mathrm{Ex_{CH}} + \mathrm{Ex_{elec}} \quad (3)$$

The reference state (temperature, pressure and chemical composition) is usually the environment in which the system operates [30, 31]. From a theoretical standpoint, the reference environment must be in thermodynamic equilibrium, and therefore, with no usable energy [32].

Exergy: Development of the method

Energy and exergy flows in the present study are limited to their thermal, chemical and electrical components. The kinetic and potential energies and exergies are neglected because their calculation involve a high level of detailed information about the process P&ID (process and instrumentation diagram), distances between equipment and so on, which are unavailable for the current study. This assumption is reasonably valid and does not significantly deteriorate the results of the exergy efficiency analysis as supported by Skogestad [33] and Peters *et al.* [34], because the friction losses are assumed negligible for the operating rates and velocities in the mill at steady state. Systems with no kinetic, thermal or potential energy are considered to be in equilibrium with the environment, and systems without chemical exergy (nor the physical, thermal or potential stated earlier) are considered to be at the dead state [9] [35, 36] and cannot produce any work [37-40].

Exergy depends on the reference chosen. The standard reference for temperature and pressure is that defined by Szargut [27] at 298.15 K and 1 atm, respectively. However, given that the external conditions vary temporally and spatially, it is recommended to chose the reference temperature in regards with the external conditions of the system under study [41]. Thus, the reference temperature chosen for the present study is 275.15 K. The reason is that the large amount of fresh water consumed in the Kraft mill has a temperature near 275.15 K which is the ambient temperature of river water in Canadian winter conditions.

The exergy balance can be expressed as:

[9] The dead state refers to the state at which a system and its environment are at mechanical, thermal and chemical equilibrium.

$$\mathrm{Ex} = \sum_i (e_{th,i} + e_{CH,i} + e_{elec,i}) \qquad (4)$$

The electrical energy is assumed fully convertible to work [24]; therefore the specific electrical energy consumed during processing (Electrical MW of energy) is equal to the specific electrical exergy $e_{elec,i}$. The specific thermal exergy $e_{th,i}$ of a stream, in regards with the reference temperature T_0 [10] chosen for the study (275.15 K) is calculated from the following equations [42]:

$$e_{th,i}(T_i, T_0) = \int_{T_0}^{T_i} Cp_{0,i}(T')(1 - \frac{T_0}{T'})\, dT' \qquad (5)$$

Or more simply,

$$\begin{aligned} e_{th,i}\,(T_i, T_0) &= e_{th,i}\,(T_i) - e_{th,i}\,(T_0) \qquad (6) \\ &= h_{th,i}\,(T_i) - h_{th,i}\,(T_0) - T_0 * [s_i\,(T_i) - s_i\,(T_0)] \end{aligned}$$

Entropy is generated when separated streams come together to form a mixture, ideal or not. An ideal mixture is an homogeneous one in which the elements are completely intermixed and all its constituent molecules have the same average energy level of interactions [43]. For ideal fluid mixtures (liquids and gases), the entropy generated due to process irreversibility (temperature and pressure gradient which are the driving forces of the process) is given by:

$$\begin{aligned} S_{gen} &= T_0 * [s_i\,(T_i) - s_i\,(T_0)] \qquad (7) \\ &= T_0 * Cp\,(T_i - T_0) * \ln\left(\frac{T_i}{T_0}\right) - R * \ln\left(\frac{P_i}{P_0}\right) \end{aligned}$$

For incompressible fluids, the term ln(Pi/P0) approaches zero. The chemical exergy of a substance $e_{CH,i}$, (of equation (4)) can be obtained from standard chemical exergy tables with the specification of the reference environment chosen, available in Szargut *et al.* [27]. For ideal mixtures containing gases other than those in the reference tables, chemical exergy can be evaluated by using the following equation [44]:

[10] The subscript zero in this paper indicates properties at the dead state at P_0=101.325kPa and T_0=298.15K.

$$e_{CH,i} = \sum x_n (e_{CH})_n + RT_0 \sum x_n \ln x_n \tag{8}$$

In equation 8, x_n is the mol fraction of the gas and R is the universal gas constant. The term $RT_0 \sum x_n \ln x_n$ represents the entropy of mixing and is always negative. The mixtures occurring in this analysis are assumed non-ideal. However, an equivalent concept for non-ideal mixtures is not available; thus, the equation for ideal mixtures has been used [45]. This will introduce errors in the calculations as the term of entropy of mixing in equation (8) does not contain the activity coefficient of the different components of the mixture [44]. However, the impacts of these errors on the final results will be considered negligible as suggested by Wall [46] . In fact, this assumption would have been invalid for systems that contain distillation columns, where the coefficient of activity of the different components in the mixture is a very important factor in the calculation of the exergy balance [47] and of the exergy of separation of the mixture. This is not the case of the Kraft process. The main mixing operations in the Kraft process are the dilution or pulp thickening, and evaporations. Hence, the variation in the entropy of mixing does not significantly vary in these types of processes (the difference between the input and output streams is only the composition), which makes the assumption reasonable for the present study.

Exergy enters at any location in the process, at a given level and may exit under three forms depending on its thermodynamic efficiency: lost and no longer available for use within the system, destroyed, and efficiently used to form the products. Therefore, the total exergy balance around the process is expressed as follows:

$$Ex_{In} = Ex_{Product} + Ex_{Lost} + Ex_{Dest} \tag{9}$$

The exergy efficiently used is the exergy of product streams sent to a subsequent unit operation for further treatment. The exergy destroyed within the system represents the entropy generated during the process and is no longer available for use while the exergy lost is composed of the available energy of the various effluents.

Considering that all real processes are irreversible, there must be a minimum amount of entropy generated to maintain the minimum driving force required to operate the process at a desired rate, and this entropy generation implies that some exergy is destroyed. The minimum amount of entropy generation necessary for the process to take place at a desired rate equals the minimum amount of exergy destroyed during process operation. This is what we call the minimum inevitable exergy destroyed. The minimum inevitable exergy destroyed (or minimum entropy generation) varies from one process to another and depends on the type of equipment and technology used, and on the operating conditions. The exergy destroyed can therefore be reduced by changing the technology (or equipment) or improving the operating conditions of the existing equipment. The best available technologies and modern equipment use significantly less energy than older ones [48]. Entropy generation is minimized in newer equipment through several ways: minimum friction losses, minimum pressure drops, better control of boundary conditions and, operating close to adiabatic conditions. The entropy generation could be lowered by 20-40% by changing the technology or the design of equipment [49].

The exergy lost is found in effluents and stack gases where the exergy content (available high quality and quantity of energy) could be upgraded or valorized, this is what we call the maximum amount of avoidable exergy loss. Through the identification of the minimum amount of exergy destroyed in each process and the maximum avoidable exergy losses, practical improvement can be developed and implemented.

The exergy efficiency definition used herein is that introduced by Fratzcher (equation (2)). This definition has been adapted to the Kraft mill unit operations and to the product streams. Effluents and stack gases have been identified for all major equipment and the seven process departments. Tables 4-1 and 4-2 display the exergy efficiencies of major equipment and mill departments. Similarly, the percentage (or ratio) of exergy destroyed and exergy lost in each major equipment and department have been computed accordingly with the equations 10 and 11 respectively.

$$\mathrm{Ex_{Dest}}(\%) = \frac{(\sum \mathrm{Ex_{In}} - \sum \mathrm{Ex_{Out}})}{\sum \mathrm{Ex_{In}}} * 100\% \tag{10}$$

$$\mathrm{Ex_{Lost}}(\%) = \frac{\sum \mathrm{Ex_{waste}}}{\sum \mathrm{Ex_{in}}} * 100\% \tag{11}$$

Thermodynamically efficient unit operations or equipment have the lowest exergy destruction ratios. Those areas should be investigated in terms of equipment condition, quality of maintenance and operating conditions. Thermodynamically efficient processes have the lowest exergy lost ratios, which means that exergy content is well managed and internal heat recovery is well performed. The maximum practical potential of savings with minimum investment cost in the process is the sum of the total maximum avoidable exergy lost. The percentage of minimum inevitable exergy lost of the mill indicates how well the equipment and unit operations are performing thermodynamically. This percentage could be lowered by 5, 10 or 20% depending on the technology used and the investment budget allowable by minimizing the entropy generation during operation [49].

Table 4-1: Exergy efficiency calculation for the different system components

Unit operation	***Exergy efficiency*** $\boldsymbol{\eta_{ex} = \frac{Ex_{product}}{Ex_{input}}}$
Shell and tube heat exchanger	$\eta_{ex} = \frac{Ex_{Hot\ Stream\ Out} + Ex_{Heated\ stream}}{Ex_{Hot\ Stream\ In} + Ex_{Cold\ Stream\ In}}$
Cooking vessel	$\eta_{ex} = \frac{Ex_{Impregnated\ wood}}{Ex_{wood} + Ex_{steam} + Ex_{WLHeated}}$
Steaming vessel	$\eta_{ex} = \frac{Ex_{WBL} + Ex_{Pulp} + Ex_{1extraction-WBL} + Ex_{2extraction-WBL}}{E_{wood} + E_{WLHeated}}$
Brown stock washer	$\eta_{ex} = \frac{Ex_{Wash\ Water} + Ex_{Washed\ Pulp}}{Ex_{Warm\ Water} + Ex_{Pulp} + Ex_{WW1} + Ex_{WW2} + Ex_{WW3}}$
Evaporators	$\eta_{ex} = \frac{Ex_{Condensed\ Water} + Ex_{Concentrated\ Black\ Liquor}}{Ex_{steam} + Ex_{WBL}}$
Recovery boiler	$\eta_{ex} = \frac{Ex_{steam} + Ex_{smelt} + Ex_{Blowdown\ Water} + Ex_{Exhaust\ Gases}}{Ex_{Hot\ Water} + Ex_{Combustion\ Air} + Ex_{CBL}}$
Bark boiler/Oil boiler	$\eta_{ex} = \frac{Ex_{steam} + Ex_{smelt} + Ex_{Blowdown\ Water} + Ex_{Exhaust\ Gases}}{Ex_{Hot\ Water} + Ex_{Combustion\ Air} + Ex_{NG}}$

To synthesize, the method herein presents the stepwise procedure that has been formulated:

1. Data collection for mass and heat balance.

2. Computation of the exergy content of all streams involved, based on reference environmental conditions chosen.
3. Identification of the streams: product streams and effluent streams.
4. Computation of exergy efficiencies, exergy lost and exergy destroyed ratios.
5. Identification of thermodynamic inefficiencies in the process and identification of the maximum avoidable exergy destruction and the minimum inevitable exergy loss in each equipment and department.
6. Proposal of practical improvement projects recommendations to the mill.

Table 4-2: Exergy efficiency calculation for the different departments of the mill

Department	***Exergy efficiency*** $\boldsymbol{\eta_{ex}} = \frac{Ex_{product}}{Ex_{input}}$
Digester	$\eta_{ex} = \frac{Ex_{pulp} + Ex_{black\ liquor}}{Ex_{electricity} + Ex_{WL} + Ex_{steam} + Ex_{wood\ chips} + Ex_{Wash\ Liquor}}$
Washing/screening	$\eta_{ex} = \frac{Ex_{washedpulp} + Ex_{Wash\ Liquor}}{Ex_{electricity} + Ex_{Warm\ Water} + Ex_{pulp} + Ex_{Wash\ Liquor}}$
Bleaching	$\eta_{ex} = \frac{Ex_{bleachedpulp}}{Ex_{electricity} + Ex_{steam} + Ex_{pulp} + Ex_{Chemicals} + Ex_{Wash\ Liquor}}$
Paper machine	$\eta_{ex} = \frac{Ex_{pulp}}{Ex_{electricity} + Ex_{MechPulp} + Ex_{Kraftpulp} + Ex_{steam}}$
Evaporation plant	$\eta_{ex} = \frac{Ex_{BL}}{Ex_{electricity} + Ex_{steam} + Ex_{WBL} + Ex_{FW}}$
Recovery boiler	$\eta_{ex} = \frac{Ex_{steam} + Ex_{smelt}}{Ex_{electricity} + Ex_{steam} + Ex_{HW} + Ex_{BL} + Ex_{air}}$
Bark boiler/Oil boiler	$\eta_{ex} = \frac{Ex_{steam}}{Ex_{electricity} + Ex_{bark} + Ex_{oil} + Ex_{HW} + Ex_{air}}$
Recausticizing	$\eta_{ex} = \frac{Ex_{WL} + Ex_{Limemud}}{Ex_{electricity} + Ex_{Lime} + Ex_{smelt} + Ex_{WashLiquor} + Ex_{Water}}$

4.6 Results and Discussion

The preliminary evaluation of energy and water consumption of the Kraft mill studied shows signs of poor performance which was a motive for further exergy analysis to propose performance improvement projects. The thermodynamic evaluation method proposed permits a straightforward application of the exergy concept to the Kraft pulp process and the identification of practical improvement projects achieving the true maximum savings. The Kraft mill was analysed using the above relations (tables 4-1 and 4-2). The entropy generation and exergy efficiency were computed for each process component as well as for the whole system. Figure 4-2 shows the results of the overall exergy efficiency computed and the exergy flows through the overall Kraft process.

The exergy content of end products accounts for 20% of the total input exergy. The overall entropy generation of the process accounts for 45% of the exergy input. The exergy losses which correspond to the exergy of effluents and flue gases account for 35% of the total exergy of the system. These results indicate that the maximum potential exergy savings of the process equal 35% of the total exergy input to the process. The exergy efficiency analysis of the system components will give more insight into where potential savings are possible and which sections are the least thermodynamically efficient.

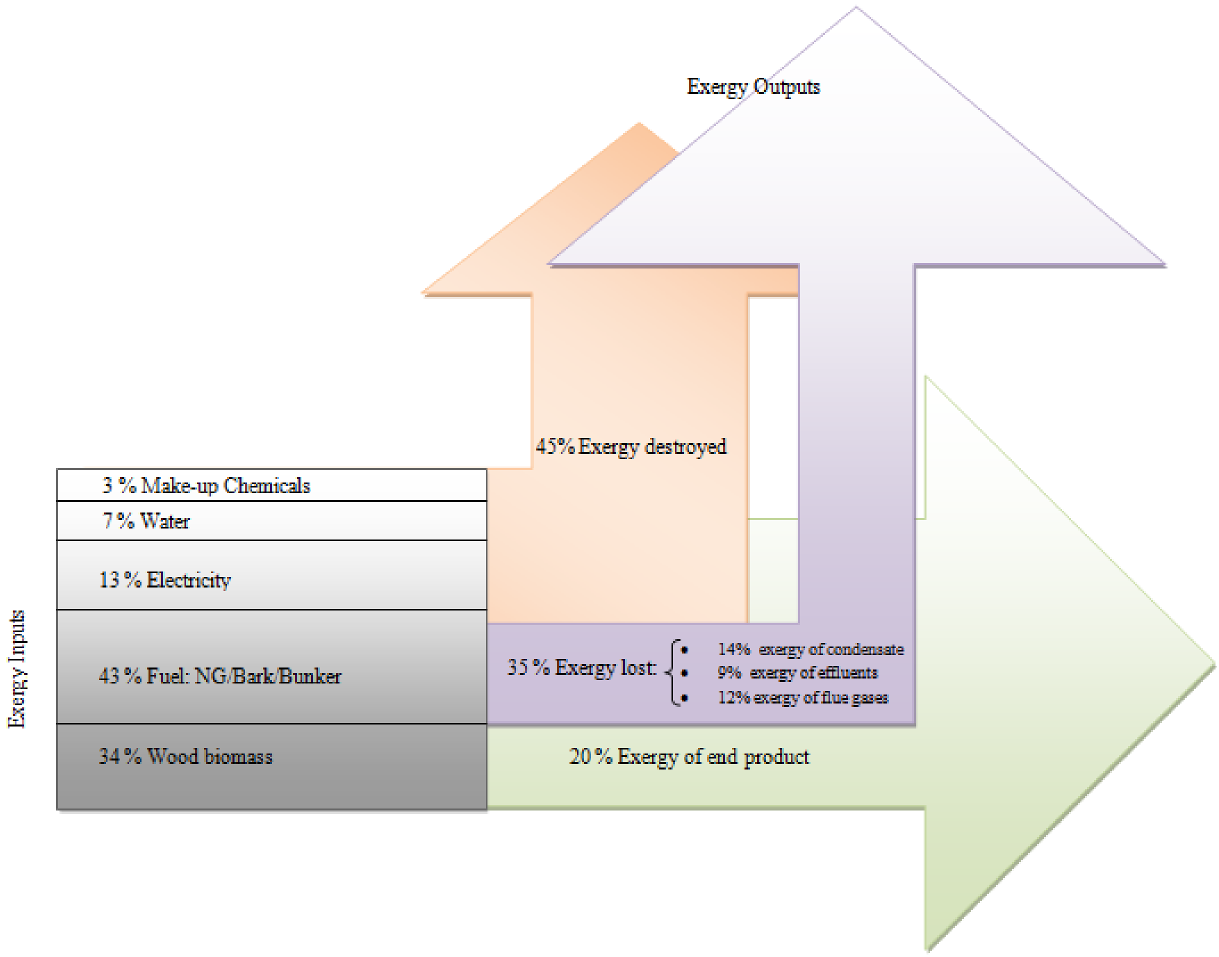

Figure 4-2: Overall exergy efficiency of the case-study mill

Figure 4-3 shows the percentage of exergy destructions and losses in the different departments of the mill, and figure 4-4 shows the exergy flow rates going into and coming out of the departments. Figure 4-3 identifies the areas having the largest percentage of exergy destruction and figure 4-4 highlights the quantity of exergy destroyed during the operation of individual departments.

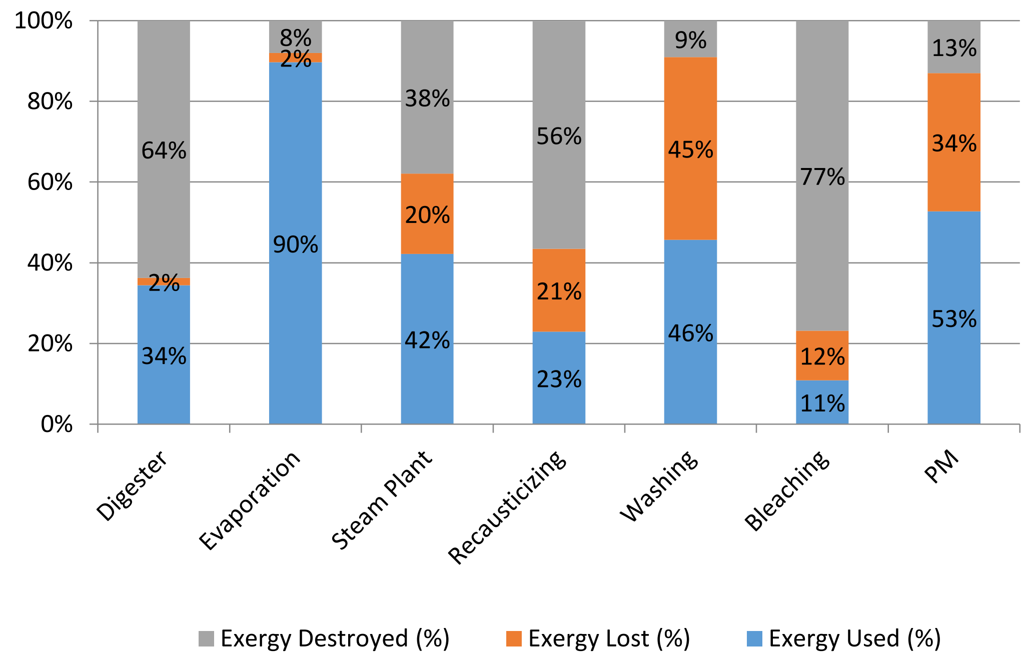

Figure 4-3: Exergy efficiency analysis per department and for the entire mill (%)

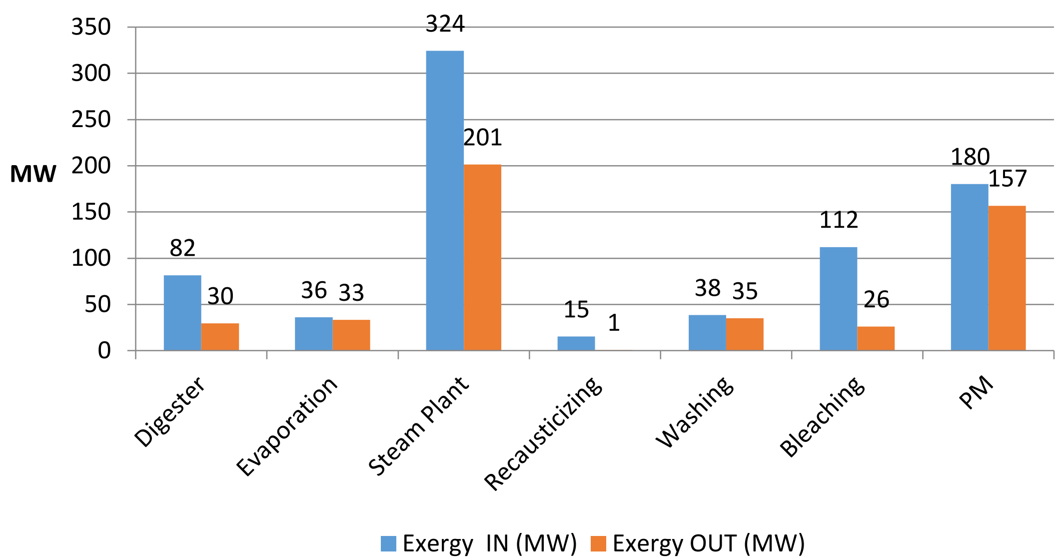

Figure 4-4: Overall exergy flow per department (MW)

The highest exergy destructions both in percentage and in quantity are in the power plant, in the bleaching, the digester and the recausticizing departments.

These results are explained by the fact that in these departments, chemical reactions take place. This contributes to increasing the irreversibility of the process and the entropy generated. In these exergy transformation departments, the entropy generation sources are many; the chemical reactions, fluid friction, free expansion of the gas (blowdown), heat transfer at finite temperature difference, phase change, and mixing of dissimilar fluids (with respect to composition or temperature).

On the other hand, the evaporator plant, the washing and the paper machine departments are areas where either mass or heat transfer occur. The fibers or cooking liquor go through these processes chemically unchanged, i.e. as transit exergy with no chemical reaction but rather a phase change. The entropy generation in exergy transiting areas is due to: fluid friction, mixing of dissimilar fluids, heat transfer across a finite temperature and heat dissipation to the environment, and phase change.

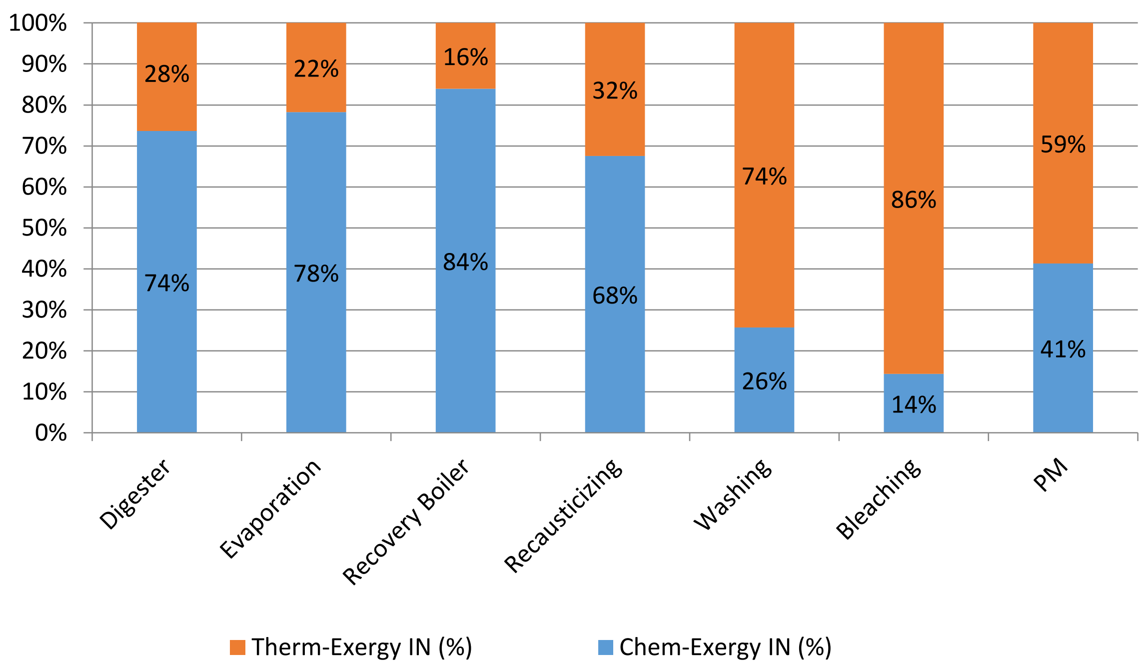

Figure 4-5: Type of exergy flow entering the different departments of the mill

The type of exergy flowing into and out of process elements provides information about the exergy transformation (energy conversion) areas and characterizes the exergy contents of the streams. Figures 4-6 and 4-7 display the type of exergy going into and coming out of unit operations of the mill. The departments where the most significant exergy transformations take place are also the sites of largest exergy destructions. The least thermodynamically efficient departments were highlighted for further investigations in order to identify the equipment or unit operation causing the inefficiency.

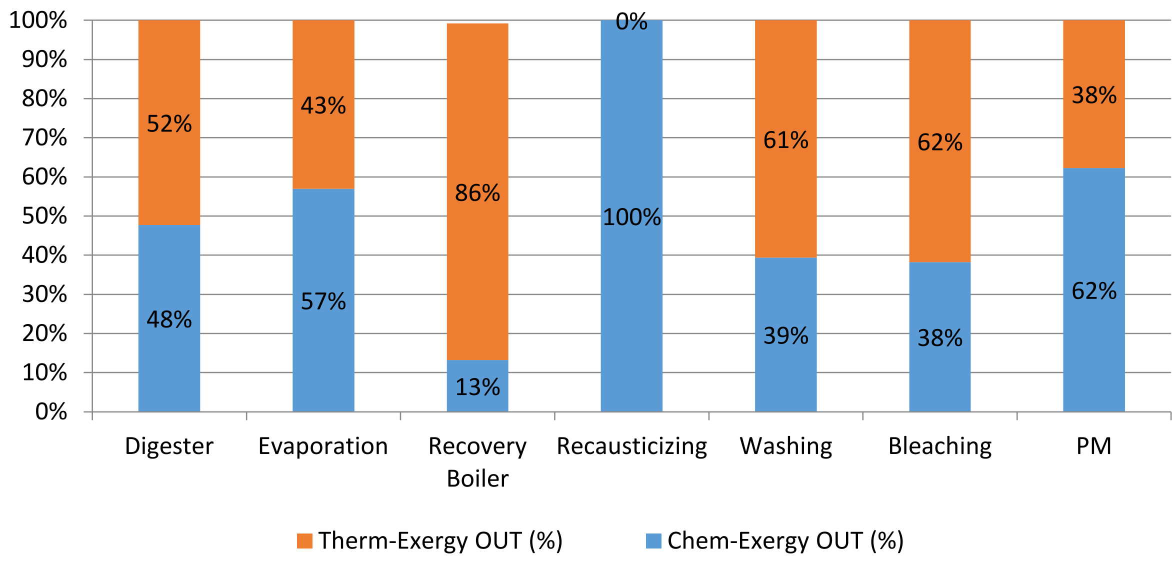

Figure 4-6: Type of exergy flow leaving the different departments of the mill

Power Plant

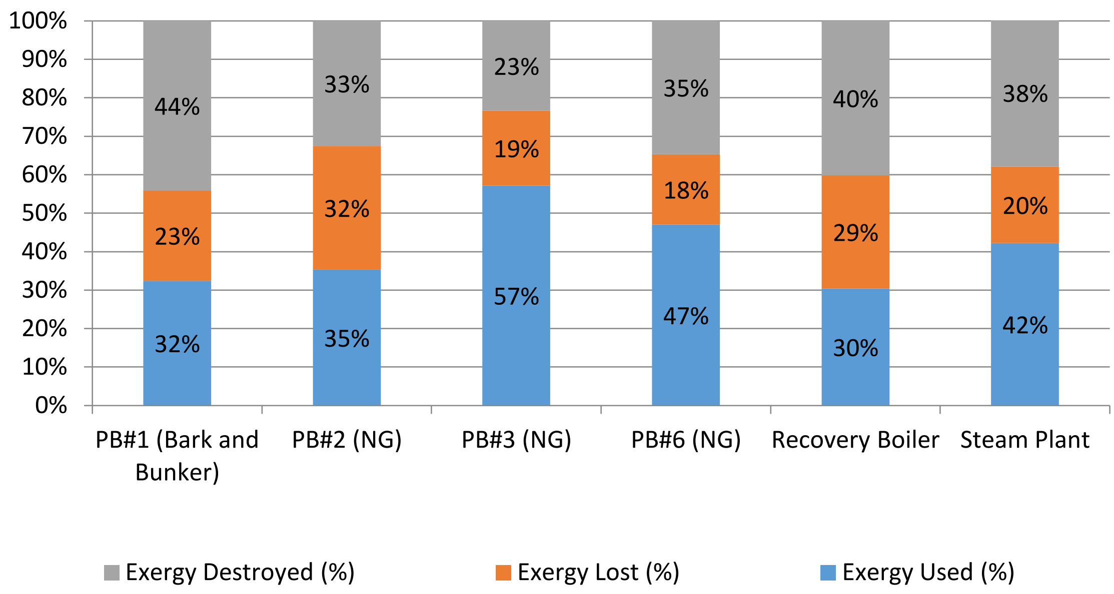

Figure 4-7: Exergy efficiency for the power plant and its major equipment

The power plant produces steam at an exergy efficiency of 42%. The main cause of this low efficiency and large exergy destruction (38%) is the irreversibility of the combustion reactions. Also, the high temperature of the stack gases exiting the boilers (20% of the input exergy) contributes to the reduction of the exergy efficiency. Exploiting the thermal exergy content of the stack gases will improve the boilers' efficiency, however, their temperature should not be reduced below a certain level otherwise condensation of sticky and corrosive matter would lead to other severe problems. Because of the large quantity of exhaust gases and their high temperature, the power plant accounts for the largest exergy loss of the mill. Improving the maintenance of the boiler-tubes will decrease the heat transfer resistance and clean tubes in the boilers contribute to a better heat transfer and therefore less exergy lost. Improvements of heat transfer effectiveness of a few percent can lead to significant reductions in natural gas consumption and the operating costs [50]. The improvements measures include enhanced tubes cleaning, improved process control on air-to-fuel ratio, reduction of exergy dissipation to the environment, and improved heat retention inside the furnace (increased heat transfer by radiation).

To improve the cleaning of tubes, the soot blowing pressure should be increased by increasing steam inlet (velocity increase) or by reducing the nozzles diameters. Superheated steam far above the saturation point is recommended for use in the soot blower to improve cleaning efficiency and avoid impingement corrosion of the tubes that would lead to higher entropy generation over time. It is otherwise, not recommended to use superheated steam because it generates more entropy than saturated steam, however, in the case of the soot blower and the boiler-tubes cleaning, the damage in the tubes generates more entropy over time. The condensate droplets (if saturated steam is used) have a higher friction than vapor and their impact on tube erosion over a long period of time is a serious problem. It is usually the main cause of inefficiency in industrial boilers. The boiler tubes could be damaged and the maintenance and cleaning are in some cases unproductive, thus, the replacement of the tubes is highly recommended for this case study.

Air-to-fuel ratio is a very important parameter in order to increase the efficiency of the boiler and reduce the exergy destruction and entropy generation. The air-to-fuel ratio should also be investigated as it has been demonstrated that the higher this ratio is, the less efficient is the boiler. An optimum ratio must be maintained constant. Maximum adiabatic flame temperature is achieved at stoichiometric conditions (oxygen to fuel ratio) and decreases as excess air is increased, it is important to mention that even small quantities of excess air reduce the adiabatic flame temperature significantly [51], which reduces the heat available for transfer through radiation and convection (via the combustion flue gases). However, insufficient excess air implies a possibility of incomplete combustion. During incomplete combustion, less heat is released and more pollutants are produced which reduces the thermodynamic efficiency of the boiler and increase its environmental footprint [52].

To reduce the exergy loss percentage of the steam plant, blowdown water from the recovery boiler, the bark boiler and the natural gas boilers' that contains high exergy content must be exploited. It could serve to preheat the colder streams in the mill. For instance, blowdown water could be sent to a flash tank to produce low pressure steam and preheat the inlet combustion air used in the boilers, This increases the exergy efficiency of the steam plant in two ways: warmer combustion air increases the adiabatic flame temperature and therefore increases the efficiency of the boiler, and the avoided exergy loss through the recovery of the exergy content of the blowdown water also increases the efficiency of the power plant.

Figure 4-7 shows the exergy efficiency of the 4 power boilers and the recovery boiler of the mill power plant. These results show that the recovery boiler and the bark boiler, both fired with biomass (lignin and bark, respectively) are less exergy efficient than natural gas boilers. This could be explained by many factors. First, the biomass boilers have an increased tendency of fouling because of the non process elements and the chemical components present in the biomass fuel, which increases the friction and reduces the heat transfer. Moreover, the biomass boilers are usually operated with higher air to fuel ratio, because the biomass fuel heating content is less stable than conventional fuel such as natural gas. It is also more complex to control [53]. An increased air-to-fuel ratio, combined with reduced available heat for transfer induce an increased entropy generation, which explains why the biomass boilers create more exergy destruction ratio than the conventional natural gas boilers.

It must also be noted that, the three natural gas boilers of the mill have different efficiencies. The PB # 3 is more efficient than the PB # 6, PB # 2 and PB# 1. The former is operated at its maximum capacity because it is more efficient than the three others. The improvement projects in the recovery boiler and the bark boiler (replacement of the heat exchangers, recovery of the blowdown water and the fuel gases exergy content and improve insulation) will increase the steam generation by approximately 30 MW. This increase will suffice to shut down the least efficient power boilers (PB # 6, PB # 2), and provide new savings for the mill avoiding the purchase of costly fossil fuel.

Digester

The digester department is where both chemical reactions and heat transfer take place and accounts for a large quantity of exergy destruction. The detailed exergy analysis of the department is presented in figure 4-8 and shows that the steaming vessel is responsible for most of the exergy destruction. The main reasons for this large exergy destruction and high entropy generation are the operating characteristics of the steaming vessel: high pressure superheated steam is injected into the woodchips. The entropy generation sources in this type of equipment are the superheated condition of the steam which favors entropy generation, the heat transfer across a large temperature gradient, the mixing of dissimilar fluids and the friction between these fluids in direct contact (change in viscosity, composition, temperature, structure and phase). For the case study, these are inevitable exergy destruction sources. However, the exergy of the steam condensate is not exploited thus lowering the process exergy efficiency. If the steaming vessel is well isolated (adiabatic conditions), the heating requirement may be reduced and impregnation may be accomplished without extra live steam (which is the current state of the mill) and fulfilled by the steam flashed in the black liquor flash tanks. This represents an avoidable exergy loss. Figure 4-9 shows the exergy improvement potential of the digester department if the steaming vessel and the chip bin are well isolated and maintained, and the exergy content of the effluent out of the surface exchanger is exploited. A total of 12.5 MW could be saved in this department provided that the maximum avoidable exergy loss is recovered.

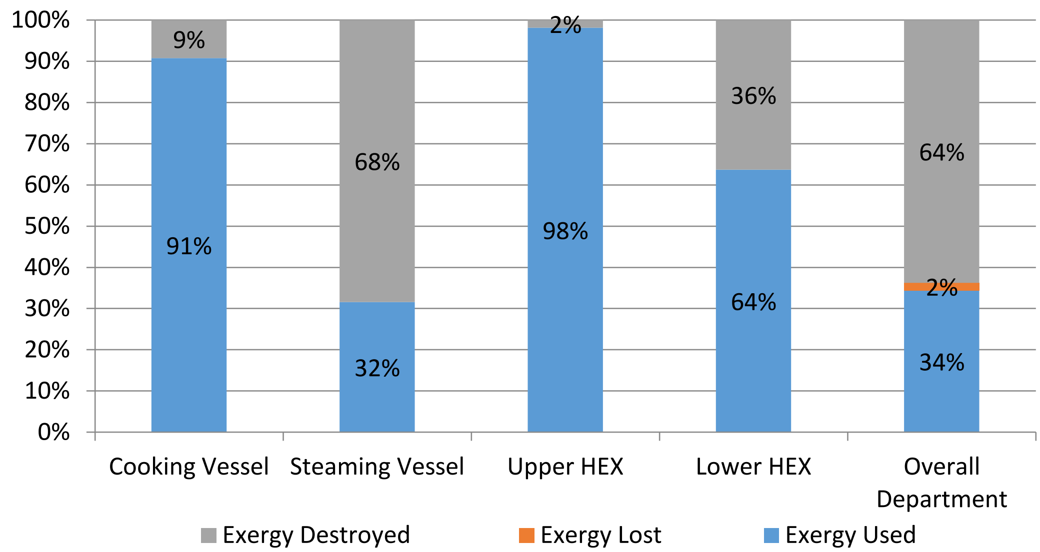

Figure 4-8: Exergy efficiency for the digester department and its major equipment

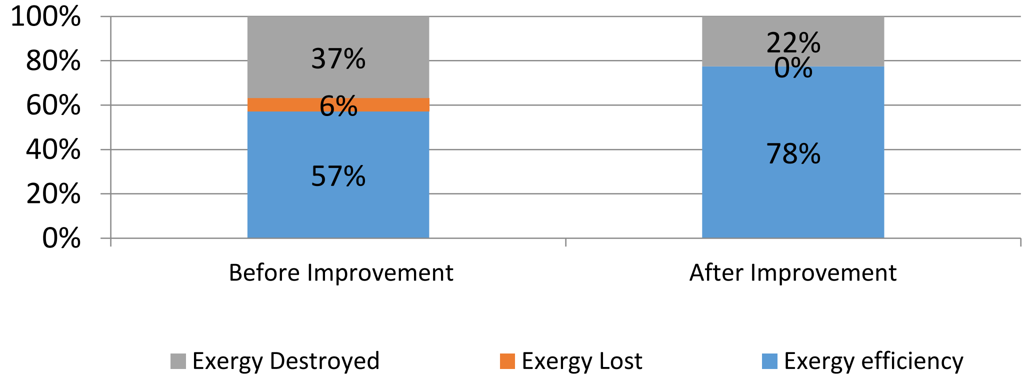

Figure 4-9: Digester's thermal exergy efficiency before and after improvement

Washing and evaporation

The washing department and the evaporation plant are exergy transiting areas. Because of the large quantities of effluents of the washing department and the high quality of exergy in the evaporation, the avoidable exergy loss is large in these two departments and there is a significant potential of improvement if their exergy content is recovered. This is possible, for example, through redesigning the heat exchangers network. Moreover, the entropy generation in these departments is low (the lowest of the mill), which indicates that the entropy generation of phase change, and dilution and thickening of the pulp is much less than the entropy generation of chemical reactions. In the evaporation plant, if the exergy destruction percentage increases, this could be a probable sign of evaporators fouling or scaling due to salt crystallisation. The black liquor contains about 35% of dissolved solids, and a variation of the black liquor composition may induce scaling and fouling problems in the evaporators. This decreases the heat transfer, increases the entropy generation and exergy destruction [54]. Efficient and adequate control of operating conditions in the recausticizing department leads to a stable cooking liquor, thus avoiding problems in the evaporation plant.

Nevertheless, the exergy improvement potential of these two departments (the washing and the evaporation) is around 19 MW provided that the maximum avoidable exergy loss is recovered.

Recausticizing

The recausticizing department is another area with poor exergy efficiency (in percentage) and the exergy destruction is much higher than the exergy loss (waste to the environment). This is mainly due to the irreversibility of the chemical reactions that take place in this department. There are four main reactions in the recausticizing department: first, the slaking reaction which occurs by the addition of quick lime to water to produce calcium hydroxide, second, the causticizing reaction during which the calcium hydroxide reacts with sodium carbonate to form sodium hydroxide, the white liquor, and third, the calcining (‘’reburning’’) of calcium carbonate produced at the causticizers to regenerate the lime, in the lime kiln. The latter reaction occurs at elevated temperatures (about 800°C) [55]. The heat is provided by combustion natural gas at the lime kiln (the fourth reaction). These reactions contribute to the irreversibility of the process and the entropy generation and exergy destruction. However, the overall inevitable exergy destruction could be lowered by minimizing the avoidable sources of exergy destruction in the department. For instance, avoiding non isothermal fluids mixing as it is the case in the current design of the process, and exploiting the thermal exergy released during the slaking exothermal reaction by circulating a cooler fluid in the equipment jacket. The avoidable exergy losses of the mill correspond to the thermal exergy content of the lime kiln stack gases. The exergy improvement potential of this department is about 1 MW.

Bleaching

In the bleaching area, many reactions take place and different chemicals are involved which increases the exergy destruction and entropy generation. The exergy destruction and the entropy generated are due to the irreversibility of the reactions and the mixing of different chemical components. On the other hand, the exergy loss is due to the large quantity of effluents generated at medium to warm temperatures. There are also steam injection points to increase the temperature of the pulp throughout the bleaching sections. These injection points are source of high entropy generation and should be completely avoided when possible. An alternative is to reuse the exergy content of the effluents generated to heat the pulp. This would minimize steam use, and also exergy destruction. The maximum avoidable exergy destruction in this department is about 12 MW, provided that the avoidable exergy losses are recovered.

Summary of results

To synthesize, the total maximum avoidable exergy lost in the Kraft pulp is 35% or 125 MW. The savings are possible through replacement of pieces of equipment in the recovery boiler and the power boilers, exploiting the exergy content of flue gases from the boilers and the lime kiln, and of the effluents from the washing plant, the bleaching department and the evaporation department. The recommendations proposed to the mill in order to minimize the entropy generation in the plant are to avoid mixing of dissimilar fluids whenever possible (the fluids can be dissimilar with respect to temperature, pressure, or composition), avoid steam injection, operate at adiabatic or/and isobaric conditions (increase isolation and reduce pressure drops), reduce fluid friction by preserving a good maintenance of the pipelines and heat exchangers, and avoid free expansion of gases (blowdown and explosion) and flow throttling. The proposed enhancement measures entail investment costs and should be economically investigated in order to evaluate their economic feasibility. Table 4-3 summarises the improvement potential for each department in percentages and quantities.

Table 4-3: Breakdown of exergy improvement potential per department

	Exergy Improvement (MW)	**Exergy Improvement (%)**
Digester	12.5	15%
Washing	17	43%
Bleaching	14	12%
Paper Machine	48.5	27%
Evaporation	2	6%
Steam Plant	30	9%
Recausticizing	1	1%
Total (MW)	**125**	**35%**

4.7 Conclusion

The quantification of exergy destroyed and lost in the process is a straightforward way to monitor the energy degradation in the process. In the case study mill, the power plant, the digester and the bleaching departments are shown to be the most inefficient areas. More precisely, the recovery boiler and the steaming vessel are the equipment responsible for the most important exergy destruction. Exergy analysis identifies thermodynamically inefficient areas. Some good engineering practices might help reduce exergy destruction like avoiding direct heat transfer when possible; avoiding non isothermal mixing when possible; reducing heat transfer resistance for indirect heat exchangers by adequate cleaning, avoiding valves in the steam pipelines, exploiting the thermal content of pressurized saturated water by sending them to flash tanks and exploiting thermal exergy of stack gases and warm effluents.

The utilization of exergy analysis strengthens the grasp of existing energy inefficiencies of the process. Exergy analysis, as showed in this study, indicates the practical and possible savings that can be achieved in the process by internal heat recovery and water reutilization, and entropy generation reduction. The application of an exergy analysis provides insight on the resource management for the long-term planning of an efficient and sustainable plant. However, exergy studies should be done in conjunction with other optimization techniques and more specific key performance indicators and equipment performance evaluation to complete the analysis.

4.8 Nomenclature

Adt	Air dry ton of pulp
Cp	Heat capacity (kJ/kg/C)
Ex_{tot}	Total exergy content of a stream (W)
Ex_p	Potential exergy of a stream (W)
Ex_k	Kinetic exergy of a stream (W)
Ex_{tot}	Thermal exergy of a stream (W)
Ex_{CH}	Chemical exergy of a stream (W)
Ex_{elec}	Electrical exergy of a stream (W)
$Ex_{CH,i}$	Chemical exergy of i component in a stream mixture (kJ/kg/s)
$Ex_{product}$	Exergy of the output streams (W)
Ex_{waste}	Exergy of the waste streams, effluents, emissions and/or stack gases (W)
Ex_{dest}	Exergy destruction streams, entropy generated during the process (W)
Ex_{in}	Exergy input into a system (W)

Ex_{out}	Exergy output of a system (W)
e	Exit streams
h	Specific enthalpy (kJ/kg)
H	Enthalpy of a stream (kJ)
Odt	Oven dry ton
o	Output flow rates
P_i	Pressure of the stream at the "i" state (Pa or atm)
P_0	Ambient pressure, pressure of the stream at the equilibrium state (1 atm)
R	Gas constant (Pa*m^3/kmol/k)
s	Specific entropy (kJ/kg)
S	Entropy generated (kJ)
T_i	Temperature of the stream at the "i" state (C or k)
T_0	Ambient temperature, temperature at the equilibrium state (25 ˚C)
η	Exergy efficiency (%)

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CHAPTER 5. ARTICLE 3: EQUIPMENT PERFORMANCE ANALYSIS OF A CANADIAN KRAFT MILL. PART I: DEVELOPEMNT OF NEW KEY PEROFRMANCE INDICATORS (KPI)

5.1 Presentation of the article

This paper has been submitted to the Chemical Engineering Research and Design in two parts, and presents a systematic methodology for evaluating Kraft process operations by means of new key performance indicators (KPIs), that take into account the governing operating parameters and the design characteristics of the unit operations. In part I, the development of new key performance indicators based on dimensional analysis of Kraft process equipment is presented. In Part II, the application of the equipment performance analysis by means of new key performance indicators (KPIs) is presented.

5.2 Abstract

Equipment performance analysis by means of key performance indicators is a prerequisite step before undertaking any optimization or improvement measure. However, there are no key performance indicators specific to the Kraft process equipment that take into account both the governing operating conditions and the design parameters. In this paper, new Key Performance Indicators (KPIs) have been developed based on an in depth characterization and dimensional analysis of the Kraft process equipment using the Buckingham Pi (Π) theorem. These KPIs were used to identify process inefficiencies, diagnose causes of inefficiencies and propose remedial actions through a systematic approach. Once adopted, the KPIs proposed could serve to monitor systems performances and allow a closer process control as they incorporate the design characteristics of the unit operations and their operating conditions.

Keywords: Kraft process, dimensional analysis, equipment performance analysis, key performance indicators, Buckingham Pi theorem.

5.3 Introduction

Improving energy efficiency in chemical industries has become of central concern in the last few decades because of increasing and volatile energy prices as well as environmental considerations

[1, 2]. This is also the case for the Canadian pulp and paper (P&P) industry that has been facing economic challenges. To remain competitive in face of emerging pulp producing countries and at a time when the demand for paper commodities is shrinking, pulp and paper mills have to double efforts to reduce their operating costs [3]. In response to this situation, a variety of methodologies and technologies has been developed to address the energy efficiency problems and gave encouraging results [1]. However, these methodologies are applied with the assumption that all equipment and unit operations are working efficiently or as intended, which is not always the case in an operating pulp and paper mill [4]. Therefore, key performance indicators that identify process inefficiencies and areas of most likely gains should be formulated at the earliest stage of a retrofit project in order to channel efforts and ensure good success of the development, the assessment and the selection of enhancement alternatives. An in-depth and careful performance evaluation analysis will later reduce commitment of expenditures, efforts, cost and deployment of resources [5]. Performance of individual equipment and department should be analyzed as a first step of each energy efficiency and water management program. The conventional way to evaluate the performance of specific equipment and unit operations is through the use of key performance indicators (KPI). The use of indicators as a calibration tool is a common practice to measure the variability and correct the functioning of a process. Key performance indicators, when used appropriately and when they are adapted to the operations investigated, can rapidly identify areas that have savings opportunities [4].

In previous publications, the performance evaluation of a process is often based on a comparison of its efficiency to that of other similar processes through the use of indicators normalized to the production rate. Francis *et al.* [6, 7] proposed the utilization of fuel consumption and thermal energy consumption as energy efficiency indicators to evaluate the performance of unit operations and equipment (ex. boiler, evaporator, etc.).

Many authors such as Lang and Gerry [8], Buckbee [9], Van Gorp *et al.* [10] and others [11-16], suggested the use of different indicators to monitor directly or indirectly process performance efficiency. The proposed indicators are in some cases, based on the utility distribution, energy, water and chemical consumptions, and for other cases, based on control loops [17]. The indicators identify areas with significant deviations from target points (energy or material consumption for example) but do not provide information on what is causing these deviations.

There are no indicators that directly reflect the causes of possible inefficiencies such as equipment lacking maintenance, wrong operating conditions, process leaks, etc. Moreover, there are no indicators specific to the Kraft process equipment that take into account its intrinsic design parameters and operating conditions. Therefore, new key performance indicators specific to the Kraft process equipment should be proposed.

The development of new key performance indicators that combine the design parameters and the operating conditions is possible through the use of dimensional analysis. Dimensional analysis is a powerful analytical technique to study physical and thermodynamic processes; it facilitates the understanding of physical phenomena; simplifies the procedure of its analysis and enables diagnostics of its efficiency. It results in a complete set of dimensionless numbers (ratios) that describe a physical process and outline the conditions under which the process operates. Buckingham first introduced a stepwise procedure for the development of non dimensional numbers that describe a given process [18]. The Buckingham Pi (Π) theorem derives its name from Buckingham's use of the symbol (Π) for the dimensionless variables in his original 1914 paper [19]. Since then, efforts have been made to develop dimensionless numbers to characterize unit operations performance in a concise way. Several dimensionless numbers have thereby been developed such as the Reynolds number (Re), to describe the kind of flows in all types of fluid problems, the Froude number (Fr), for modeling flow with a free surface, Nusselt (Nu), Biot (Bi) and Peclet (Pe) to describe heat transfers, or Carnot coefficient (η) for energy efficiency, to only name a few. Several authors [20-31] used dimensionless numbers to evaluate the performance of chemical engineering unit operations. The dimensionless groups are then interpreted on the basis of a pertinent operating ratio (heat or mass flux for example) to evaluate the performance of the operation under investigation. A number of attempts have been made to produce empirical correlations that combine different dimensionless numbers, applicable to a range of operating conditions. Balocco [23] proposed an energy efficiency study for cooling and heating buildings based on dimensional analysis. Arora and Potucek [32-34] suggested the use of dimensional numbers such as Biot and Peclet to evaluate the performance of displacement washing. Brenner [34], Mcdonough *et al.* [35] and Jain *et al.* [36-38] used dimensionless numbers to evaluate the performance of the washing and the bleaching process operations. Nevertheless, no dimensional analysis on the Kraft process equipment has been published.

The objective of this work is the development of new key performance indicators based on the characterization and the dimensional analysis of the Kraft process equipment using the Buckingham Π (Pi) theorem. These KPIs will be used, in combination with other relevant indicators, for a complete equipment performance analysis. The work is presented in two parts. Part I describes the development of the new KPIs, and the results of the application of the equipment performance analysis on a Canadian Kraft mill are presented in Part II.

5.4 Context of the study: Kraft process

The Kraft process is the worldwide prevalent manufacturing process by which wood chips are transformed into pulp [39]. A simplified diagram of a complete Kraft process is displayed in figure 5-1.

Figure 5-1 : Simplified diagram of the Kraft process

The Kraft process consists of two main parts: a paper line and a chemical recovery loop. The paper line is composed of four departments; the digesting, the washing, the bleaching, and the paper making. The chemical recovery loop consists of three main departments: the evaporation, the steam plant, and the recausticizing.

The core of the Kraft process is the chemical delignification step which takes place in the digester in which the individual cellulosic fibers are separated from lignin to form the pulp. The delignification agent (called cooking liquor) is a mixture of sodium hydroxide and sodium sulfide. The pulp produced in the digester is washed in counter-current washers and then chemically bleached through a series of bleaching stages at different pH and temperature conditions and using different bleaching chemicals. The bleached pulp is then drained, pressed and thermally dried. The spent delignification liquor (black liquor), separated from the fibers in the washing step is concentrated in the multi-effect evaporators and then burnt in the recovery boiler to produce the steam required for the process and to recover the spent chemicals. The spent inorganic chemicals form a smelt that is collected at the bottom of the recovery boiler and composed of sodium carbonate and sodium sulfide. The smelt is dissolved to form green liquor and then recaustified to regenerate the delignification liquor (white liquor). Impurities introduced from the recovery boiler and the lime kiln, and non process elements introduced through the woody biomass are removed in the chemical recovery department, otherwise the overall efficiency of the mill would be compromised. The calcium carbonate is burnt in the lime kiln fired with natural gas to regenerate the lime required for recaustification [40].

5.5 Background of the dimensional analysis and the Buckingham II theorem

Dimensional analysis is an effective tool for reducing complex physical problems to a simpler form. The strength of the dimensional analysis is its ability to describe by means of dimensionless variables the process and for a broad range of scales in various designs. Dimensional analysis is based on the assumption that because all physical equations must be dimensionally homogenous, a restatement of these equations in an appropriate dimensionless form will reduce the number of parameters to treat, and thus greatly simplify the problem. It can be particularly useful in exploratory investigations of new phenomena for which the equations and boundary conditions have not yet been fully formulated [41].

Any process operation can be described by certain properties e.g. length, velocity, area, volume, acceleration, etc. These are all known dimensions, i.e. properties which can be measured. If it is possible to identify the parameters involved in a physical situation, dimensional analysis can define a relationship between them. Its use in engineering is ubiquitous and its applications are many, including astrophysics, electromagnetic theory, radiation, aerodynamics, ship design, heat and mass transfer, mechanics of elastic and plastic structures, chemical reactions and processing, etc. [42] .

The Buckingham II theorem concerns physical problems with the form:

$$y = f(x_1, x_2, x_3, \dots, x_N) \tag{1}$$

The theorem states that if the dependent variable (y) is completely determined by the values of a set of N independent physical quantities (x), with M fundamental dimensions, then the variable (y) can be completely determined by N-M dimensionless groups [43]. Dimensional analysis must be based on a complete set of independent quantities that describe the parameter of interest [42]. The use of an incomplete set of independent variables (influencing parameters of the operation under investigation) can significantly deteriorate the analysis. However, superfluous independent quantities complicate the results unnecessarily. It is important to make simplifying assumptions when possible (example of the steady-state) to simplify and limit the complexity of the problem. The proposed method permits to assess the performance of a system given its design parameters and operating at certain conditions. The detailed procedure for the application of the Buckingham II theorem is explained in the appendix of the paper. A detailed characterization and dimensional analysis based on the Buckingham II theorem of the Kraft process equipment for the purpose of development of key performance indicators, is presented in the following section. A list of the equipment and unit operations considered in this study is given in table 5-1.

Table 5-1: List of major equipment per department

Department	**Key equipment**
Digester	Steaming vessel; Heat Exchangers
Washing	Brownstock washers
Bleaching	Bleaching towers
Paper drying	Paper Machine
Evaporators - BL Concentration	Evaporators
Steam Plant	Recovery boiler; Power boiler
Chemical Recovery	Clarifiers; Lime Kiln; Causticizer; Slaker; Dregs filters

5.6 Characterization of key-equipment and dimensional analysis of the Kraft process

1. Digester: steaming vessel and heat exchangers

The digesting department is the core of the Kraft process. It consists of 4 main pieces of equipment: the steaming vessel, a cooking vessel called digester, and two heat exchangers (upper and lower). The steaming vessel is where the impregnation of wood is performed by means of direct steam injection. The cooking vessel (digester) is where the delignification step takes place and lignin is separated from the cellulosic fibers by the action of the cooking liquor, called white liquor. The two heat exchangers heat the cooking liquor extracted from the digester at two stages (upper and lower) in order to maintain an appropriate delignification temperature in the vessel, and permit a good recirculation of the cooking liquor which optimizes the delignification reactions. The digesting department is energy-intensive, consuming around 15% of the total steam requirement of the mill [44]. Figure 5-2 displays a simplified schematic of the digesting department and its main equipment.

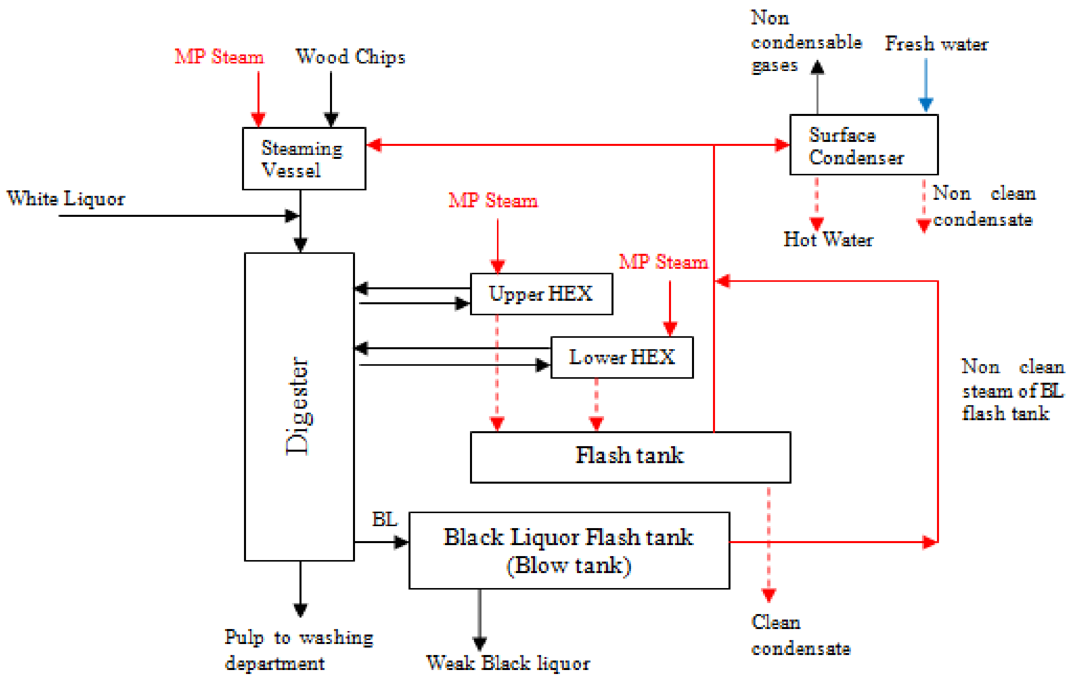

Figure 5-2: Schematic of the digesting department

The three steam users in this department are the two heat exchangers and the steaming vessel. The dimensional analysis of the department focuses on the steam users.

1.1 Steaming vessel

Assuming the steaming vessel is perfectly mixed at steady state, the independent influencing parameters characterizing the wood impregnation are summarized in table 5-2.

Table 5-2: Parameters characterising the Steaming Vessel

Parameters	***Description***	***Units***	***Dimensions***
t	Residence time	S	T
T	Temperature of woodchips (in and out)	K	ϴ
h	Convection heat transfer coefficient	$kJ/s/m^2/K$	QT-1L-2ϴ-1
k	Thermal conductivity coefficient of wood	kJ/s/m/K	QT-1L-1ϴ-1
Cp	Heat capacity (wood in and out)	$kJ/m^3/K$	QL-3ϴ-1
H_{steam}	Enthalpy of steam	KJ/kg	QM-1
m_{steam}, m_{wood}	Mass flows of steam injected and of wood chips	Kg/s	MT-1
l	Wood chips length	M	L
ρ	Density of wood	Kg/m^3	ML-3
r	Wood chips radius	M	L

The residence time (t) provides information on the amount of steam required for a given wood chips flow rate. The heat transfer coefficient (h) depends on both the thermal properties of the heating medium (steam) and the hydrodynamic characteristics of its flow, thus it encompasses all the information and parameters influencing the heat transfer. Thermal conductivity (k) and heat capacity (Cp) are intrinsic properties of wood, they determine the required amount of steam necessary for a given residence time. The density, length (l) and radius (r) of wood chips are also important parameters to be considered in the heat transfer and the impregnation efficiency; they have a direct impact on the residence time required. The characterization of the steaming vessel and the identification of the critical parameters for the dimensional analysis produced 10 independent influencing parameters and 5 fundamental independent dimensions (Q, T, M, L and Θ) and it produced five (10-5) dimensionless numbers and one pertinent ratio to be monitored:

$$N1 = \frac{Cp*T}{\rho H}; \quad N2 = \frac{r}{l} = \ aspect\ ratio; \quad N3 = \frac{t*h}{r*Cp}; \quad N4 = \frac{hl}{k} = Nu\ ; \quad N5 = \frac{t*k}{r^2*Cp}. \qquad (2a)$$

$$R1 = \frac{m_{steam\ in}}{m_{wood\ in}}\ ; \qquad (2b)$$

The number R1 represents the ratio of steam to wood flow rates entering and exiting the steaming vessel. This ratio is derived from on the heat balance around the vessel in order that the appropriate amount of steam at specific conditions of temperature and pressure is used to heat the wood chips up to a given temperature. Some dimensionless numbers have explicit physical meanings: N2 refers to the characteristic dimensions of the wood chips, and N4 represents the Nusselt number and represents heat of convection to heat of conduction. On the other hand, N1 represents the heating capacity over the enthalpy of the steam. It gives an indication on the performance efficiency of the heat transfer. The higher the value of N1, the better the steaming vessel is performing. The number N3 is the ratio of convection to heating capacity, given a residence time and a characteristic dimension of the wood chips. Similarly, N5 is the ratio of heat of conduction over heating capacity given a residence time and a characteristic dimension of the wood chips. The numbers N3, N4 and N5 give an indication of whether the convection or the conduction is the limiting factor for an efficient heat transfer in the vessel, taking into account the operating residence time and the wood chips dimensions (N2). An optimum ratio R1 that takes into consideration those dimensionless numbers can be found. The residence time (t), the dimensions of the wood chips and the steam flow rate (m_{steam}) are the parameters that will vary in order to maintain optimum KPIs.

1.2 Heat exchangers

The governing factors involved in the heat transfer in a tube and shell heat exchanger are: the heat exchange area (A), the overall heat transfer coefficient (U), the conductivity of the tubes-and-shell walls (k), the heating capacities of the cold and hot fluids, and the enthalpies of the heat transferring media. The independent parameters defining the system are given in table 5-3.

Table 5-3: Parameters characterising the Heat Exchangers

Parameters	***Description***	***Units***	***Dimensions***
A	Heat exchangers area	m^2	L2
U	Overall heat transfer coefficient	$kJ/s/m^2/k$	QT-1L-2Ө-1
Cp	Heat capacity of BL	kJ/kg/K	QM-1Ө-1
H	Enthalpy of steam in	kJ/kg	QM-1
k	Thermal conductivity coefficient	kJ/s/m/k	QT-1L-1Ө-1
m	Mass flow in and out	kg/s	MT-1

The dimensional analysis of the heat exchangers generates two dimensionless numbers with explicit physical meaning, and one pertinent ratio:

$$N1 = \frac{AU}{m*Cp} = NTU; \qquad N2 = \frac{U*\sqrt{A}}{k} \tag{3a}$$

$$R1 = \frac{mCp_{min}}{mCp_{max}} \tag{3b}$$

The number R1 represents the ratio of the heating capacities of the hot and the cold streams, and N1 represents the overall conductance over the rates of heat capacity, also designated as the number of transfer units (NTU) for the heat exchangers [45]. The performance of the heat exchanger is function of N1 and R1. Low values of R1 ratio and high values of N1 number imply a better heat exchanging performance, while N2 which is the equivalent of the Nusselt number gives an indication on the ratio of heat convection over heat of conduction given the specific characteristic heat exchange area. These dimensionless numbers (KPIs) are also valid for the evaporators since the heat transfer is performed by indirect contact through the evaporators' jacket surface area.

2. Washing: Brown stock washers

The objective of brown stock washing is to remove the maximum amount of dissolved solids (DS) from the pulp while using as little wash water as possible [46]. The DS left in the pulp will interfere with later bleaching and papermaking and will increase the costs of these processes. An inefficient washing, either because of excessive use of water, or insufficient solute removed could cause an increase in operating costs in the bleaching, the paper making, the evaporation departments and the steam plant.

There are two basic pulp washing operations: the dilution/extraction washing and the displacement washing.

In displacement washing, the liquor in the pulp is displaced with weaker wash or clean water. Ideally, for a perfect displacement, no mixing takes place at the interface of the 2 liquors. However, in practice, it is impossible to avoid a certain degree of mixing because of molecular and convective diffusion between the wash liquor and the pulp [47]. Some of the original liquor will remain with the pulp and some of the wash liquor will channel through the pulp mass. The efficiency of the displacement washing depends on the degree of mixing and also on the rate of desorption and diffusion of dissolved solids and chemicals from the pulp fibers [47]. The efficiency of the displacement washing is described by a displacement ratio (DR) and by the equivalent displacement ratio (EDR). The DR is the ratio of dissolved solid removed to the maximum amount of solids that can be removed, and the EDR represents the extrapolation of the DR to compare washers of different designs and operating conditions [48].

On the other hand, the efficiency of dilution/extraction washing depends primarily on the consistencies to which the pulp is first diluted and later thickened. This is described by the consistency of pulp (inlet and discharge consistencies) and by the dilution factor which represents the amount of water to pulp ratio.

In general, the efficiency of the washing operation is a function of many variables such as the amount of wash water, feed consistency, air entrainment, pulp porosity, thickness of pulp, viscosity, wash water distribution, and discharge consistency [49, 50]. Most of these variables are interrelated and improvement in one may have a favourable or unfavourable impact on other factors. The governing independent parameters of the washing operation are listed in table 5-4 and include pulp properties (diffusion rate D, and viscosity μ) equipment design characteristics, and the operating conditions. A total of 10 independent parameters and 3 fundamental dimensions are involved. It should be noted that pressure and temperature are important operating conditions that have not been included in the list of independent parameters considered because the rate of diffusion is a dependent function of these variables. The increase of temperature and pressure leads to a higher rate of diffusion [33].

The dimensional analysis of the washing equipment generates 7 dimensionless numbers that are required to understand the washing mechanism and evaluate its performance

Table 5-4: Parameters characterising the Washing

Parameters	***Description***	***Units***	***Dimensions***
D	Rate of diffusion	m^2/s	L2T-1
μ	Viscosity of the pulp wash	Pa.s	MT-1L-1
t	Contact wash time	s	T
v	Tangential velocity of fluid	m/s	LT-1
A	Washing area	m^2	L2
ρ	Density	kg/m^3	ML-3
w	Pulp thickness	m	L
d	Diameter of the washer	m	L
m	Pulp mass flow and wash water flow	kg/s	MT-1
ΔKappa	Cleanliness of pulp	%	NA

The dimensionless numbers are:

$$N1 = \frac{D*t}{A}; \qquad N2 = \frac{\mu*w}{m}; \qquad N3 = \frac{A}{d^2}; \qquad N4 = \frac{\rho v d}{\mu} \approx Re; \qquad N5 = \frac{D}{vd}; \tag{4a}$$

$$R1 = \frac{\Delta kappa}{m_{\frac{kg\ water}{ton\ of\ pulp\ washed}}}; \tag{4b}$$

Two dimensionless numbers, N3 and N4, have explicit physical meaning: N3 represents the characteristic design ratio of the washer, and N4 is the Reynolds number. The number N1 represents the rate of diffusion per washing area, for a given washing time. The operating conditions such as velocity of pulp and residence time should be investigated for an optimum value of N1. The number N2 represents the viscous forces over the mass flow of the pulp through the washing machine, which gives an indication on the resistance to flow. The number N5 is the ratio of the rate of diffusion over the tangential velocity of the pulp and gives an indication of which forces are dominant and which operating conditions favor the washing and the diffusion of solutes. Finally, R1 ratio represents the cleanliness of pulp over the water consumed normalized to the quantity of pulp washed. It (R1) combines the quantity of water and the amount of solute removal. R1 is selected as the main key performance indicator of the washer equipment as it is ultimately the main goal of the washing department. Thus, the operating conditions and the remaining dimensionless KPIs should be investigated in order to maximize R1.

3. Bleaching: Bleaching towers

The washed brown pulp enters a five stage bleaching process where ClO_2, O_2, NaOH, O_2 and H_2O_2 are used to produce a white pulp. The bleaching towers are described using the standard name convention for bleaching sequences; with capital letters that refer to the oxidizing/reducing chemical used, and subscripts when more than one tower uses the same bleaching chemical. Hence, ClO_2 is referred to with the capital letter D that stands for chlorine Dioxide, O_2 stage is referred to as O for oxygen delignification, NaOH is referred to as E for caustic Extraction and H_2O_2 is referred to with the letter P for Peroxide delignification. The bleaching sequence is then called D_0EOPD_1.

The objective of bleaching is to improve the cleanliness of the pulp as measured by brightness, with minimum chemical cost and environmental impact, while producing a high quality pulp. This occurs by removing or discoloring the colored substances in the pulp. Residual lignin is a major contributing factor to the color of the pulp and must be removed or brightened. Chemical pulps are usually bleached using lignin removing chemicals. The chemicals used can break down the residual lignin into small water or alkali soluble parts with the minimum effect on carbohydrates [40]. Usually, alkaline and acidic stages are used to reach targeted brightness indicated by a given Kappa number. The influencing parameters involved in the bleaching operation are the chemical consumption (kg/odt of pulp) in each stage, the temperature, the brightness via Kappa number, the COD and the pH. These parameters must be closely monitored and controlled. Sandeep *et al.* [37, 38] investigated different bleaching conditions in order to optimize the bleaching while minimizing the chemical consumption. Their work showed that; in order to optimize the bleaching, the ClO_2 charge in the D_0 stage should not be over 55-60% of the total charge, for instance D_0+D_1. The temperature at the extraction stage (EOP) should be maintained at 70˚C and pH around 11 to improve the end brightness (the usual temperature in mills is 60˚C) [51, 52]. The use of O_2 and H_2O_2 in the NaOH extraction stage improves the resulting brightness of the pulp.

It is difficult to apply the dimensional analysis on the bleaching operation because it requires the knowledge of all effective reaction rate constants [53]. These constants are not available in operating pulp and paper mills. However, the Kappa number is an indirect parameter that provides information about the bleaching reaction results. Thus, the main parameter to evaluate the performance of a bleaching stage is the dimensionless Kappa number (brightness). It is a function of the retention time in the bleaching section, and of the chemical consumption. Hence, the main dimensionless ratio for performance evaluation of the bleaching section is:

$$R1 = \frac{\Delta kappa}{m_{\frac{kg\ chemical\ consumed}{ton\ of\ pulp\ washed}}} \tag{5a}$$

The chemical consumption is defined as the amount of chemicals consumed (kg) per ton of oven dried pulp. The fully bleached pulp enters a drying process where 90% of the water is removed and dried and the paper sheet is produced.

5. Paper machine

The paper machine is a very important unit operation of the Kraft process as it is the product finishing equipment of the entire process [16]. The paper machine is constituted of three main sections: the forming section also called wet section, the press section, and the drying section. In the forming section, the slurry, a mixture of pulp and chemical additives used to promote certain properties of the final products, is evenly distributed over a perforated moving screen, the wire. The dewatering in this section occurs mainly under gravitational forces. The web enters the press section where water is removed by mechanical compression. In the third part, the web passes over rotating heated cylinders [54, 55]. Thermal energy is used alone for dewatering in the dryer section. A schematic of a paper machine is shown in figure 5-3. The thermal drying part of the paper machine is very energy intensive and is generally the largest energy consumer of the mill accounting for about 40% of the total steam consumption [44].

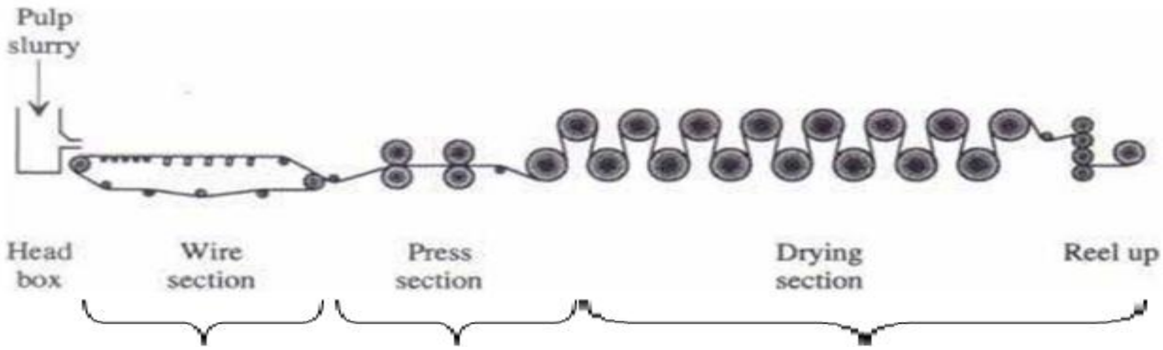

Figure 5-3: Schematic of the paper machine

The governing parameters involved in the paper machine throughout its three main sections are listed in table 5-5. The gravitational forces (g) are the only forces for dewatering in the first section. The width (w) and area (A) of paper sheet and its conductivity (k) determine the amount of heat required for drying the paper. The heat transfer by convection (h), the pressure, temperature and enthalpy of the steam (T, P, H) are important properties of the heating medium, essentially the steam. The length (l) and diameter (d) of the cylinders as well as the velocity (v) of the paper sheet through the paper machine are important design parameters and operating conditions that also determine the amount of steam required for drying the paper.

Table 5-5: Parameters characterising the Paper Machine

Parameter	***Description***	***Units***	***Dimensions***
A	Paper sheet surface	m^2	*L2*
w	Width of paper	M	*L*
H	Enthalpy of steam in	kJ/kg	QM-1
T	Temperature of steam	K	Θ
t	Residence time of paper	S	T
P	Pressure of steam	kPa	ML-1T-2
h	Convection heat transfer coefficient	$kJ/s/m^2/K$	QT-1L-2Θ-1
k	Thermal conductivity coefficient	kJ/s/m/K	QT-1L-1Θ-1
Cp	Heat capacity of paper sheet	kJ/kg/K	QM-1Θ-1
m	Mass flow	kg/s	MΘ-1
l	Cylinder length	M	L
d	Diameter of cylinder	M	L
v	Velocity of paper sheet through the paper machine	m/s	LT-1
g	Gravitational forces	m/s^2	LT-2

The characterization of the paper machine identifies one ratio that can be used for benchmarking and the dimensional analysis produced 9 dimensionless numbers.

$$N1 = \frac{gt^2}{l}; \quad N2 = \frac{v}{gt}; \quad N3 = \frac{vt}{l}; \quad N4 = \frac{Plt}{m}; \quad N5 = \frac{A}{wl} \quad N6 = \frac{d}{l}\ or\ \frac{w}{l}; \tag{6a}$$

$$N7 = \frac{PHt}{kT}; \quad N8 = \frac{hl}{k}\ or\ \frac{hA}{kw} \approx Nu; \quad N9 = \frac{H}{CpT}.$$

$$R1 = \frac{m_{steam}}{m_{evaporated}} = Steam\ economy \tag{6b}$$

The dimensionless numbers can be arranged to describe the three different constituents of the paper machine. The numbers N1, N2 and N3 describe the wire section. They take into account the gravitational forces, operating condition (v) and dimension of the wire (l). They are pertinent KPIs for the section and should be monitored and interpreted in regards of the water removed per pulp treated (kg/kg). The number N4 is the main dimensionless KPI for the press section. It represents the mechanical pressing force per characteristic length and mass flow of pulp and should also be interpreted in regards to the water per pulp removed in the section. The numbers N6 and N7 are dimensionless design ratios characterizing the equipment. The last two dimensionless numbers characterize the drying section, number N8 is the Nusselt number and N9 represents the ratio of the heat supplied over the heating capacity of the paper. The dimensionless numbers combined with the ratio (R1) of overall evaporated water to the steam used are valuable performance indicators to be monitored and integrated in the performance management strategy of the mill. The ratio R1 is used for the overall monitoring of the energy consumption in the paper making department and should be minimized in regards with the other dimensionless numbers. The value of R1 for a modern paper machine should be equal or less than 1.3 [56].

6. Evaporators

Multi effect evaporators are used to concentrate the weak black liquor by means of heat transfer before sending it to the recovery boiler. Steam is injected into the evaporator jackets and supplies the heat required to evaporate the weak liquor. The evaporated water is injected into the next evaporator unit and so forth. Hence, these evaporators in series exploit the maximum available thermal energy from the steam injected. The main parameters involved in this heat transfer operation process are similar to those obtained for the heat exchangers and consequently the dimensionless numbers produced are also similar:

$$N1 = \frac{AU}{m*Cp}; \qquad N2 = \frac{h\sqrt{A}}{k} \tag{7a}$$

$$R1 = \frac{m_{evaporated}}{m_{steam}} = Steam\ economy \tag{7b}$$

The overall ratio of evaporated water over steam injected normalized to the production rate (R1) is used for benchmarking. The value of R1 for a modern six-effect evaporator train should be equal to or higher than 5.5[56]. The two dimensionless numbers N1 and N2 describe the performance of heat transfer in the evaporator, given their design characteristic represented by the heat exchange area of the evaporator jacket (A).

7. Steam plant: Recovery boilers (RB) and power boilers (PB)

A black liquor recovery boiler has two main functions: it generates steam from the heat liberated by combustion of the organic constituents of the black liquor combusted, and the spent chemicals from pulp digesting (sulphur and sodium) are recovered from the black liquor as a smelt. The recovery boiler thus acts as a chemical reactor. This double function makes its design delicate and the evaluation of its performance complex. In addition, the recovery boiler is the bottleneck in most mills. An efficient recovery boiler is important and necessary to supply the energy required by the process.

The recovery boiler can be separated in two parts: the furnace section where the combustion reaction takes place, and the heat exchanger section where the heat from combustion gases is transferred to water.

Environmental issues and corrosion problems of stack gases from the recovery boiler have been subject to many studies. They have not been treated in the present study. Nevertheless, energy improvement of the RB induces lower environmental impacts. In an ideal recovery boiler, all the sulphur and sodium components would be transformed to sodium sulphide (Na_2S) and sodium carbonate (Na_2CO_3) and form the smelt.

In a real recovery boiler, the reduction ratio (Na_2S/total S) is typically 90-95%. A substantial part of the sulphur and sodium is carried by the combustion gases into the stack, mainly in the form of sodium sulphate dust and sulphur containing gases. These components are the cause of most side problems such as fouling of heat transfer surfaces and corrosion. The S/Na_2 ratio in the flue gas and in the smelt is a critical performance index that must be monitored. The pH-value of dust carried by flue gases is a sensitive indicator for the sulphur and sodium chemistry (before electrostatic precipitator). High pH (>10) indicates that the ratio is less than unity. Low pH<7 is an indication the ratio is high, with an increased tendency to form acidic sulphates. Thus, the S/Na_2 ratio and the pH must be monitored closely [56].

Furthermore, non-process elements such as potassium (K) are concentrated into gaseous phase in the lower furnace. This lowers the dust melting temperature and results in increased sticking and fouling effects. Non-process elements should be eliminated from the process in the causticizing department. The critical parameters to achieve sustained performance of the recovery boiler are given in table 5-6. For efficient fuel combustion, the heating value of fuel (HHV), and the amount of feed air are the dominant factors influencing the performance of the boiler. For the heat exchangers zone of the boiler, the heat exchangers area (A) and the overall heat transfer (U) are the main parameters. The black liquor droplets diameters should be maintained constant for a better control of the combustion reaction [57].

Table 5-6: Parameters characterising the Recovery Boiler and Power Boiler

Parameters	***Description***	***Units***	***Dimensions***
A	Heat exchangers area	m^2	L2
U	Overall heat transfer coefficient	$kJ/s/m^2/k$	QT-1L-2Ө-1
T	Temperatures of water and air in and steam out	k	Ө
H	Enthalpy of water in and steam out	kJ/kg	QM-1
k	Thermal conductivity coefficient	kJ/s/m/k	QT-1L-1Ө-1
m	Mass flow in and out	kg/s	MT-1
HHV fuel	High Heating Value of fuel	kJ/kg	QM-1

The dimensional analysis of the furnace generates one main dimensionless number and three indexes to monitor

$$N1 = \frac{(Hsteam - Hwater)}{HHV} \tag{8a}$$

$$R1 = \frac{mair}{mfuel}; \qquad R2 = pH; \qquad R3 = \frac{S}{Na_2}; \tag{8b}$$

The air to fuel ratio (R1) must be closely monitored for an efficient and complete combustion in the furnace section this ratio should be as low as possible, yet providing a complete combustion (excess air and the value of R1 higher than 1). The pH (R2) and the S/Na_2 ratio (R3) of the flue gas must be monitored to validate the efficiency and completion of the combustion reactions. The value of R2 should be higher than 10 and the value of R3 should be less than unity. The key performance indicator N1 represents the overall energy efficiency of the boiler. The value of N1 should be as high as possible.

The dimensional analysis of the boiler, economizer and super-heater generates two dimensionless KPIs, and one ratio to monitor:

$$N1 = \frac{AU(Tsteam - Twater)}{m*(Hsteam - Hwater)}; \qquad N2 = \frac{U\sqrt{A}}{k} \approx Nu \tag{9a}$$

$$R1 = \frac{msteam*H_{steam}}{mstack\ gases*H_{stack\ gases}}; \tag{9b}$$

The first dimensionless indicator N1 describes the maximum amount of energy that should be transferred to the water to produce steam over the real energy transferred. In other words, N1 represents the efficiency of energy transfer in the heat exchanger zone of the boiler. The second indicator is the Nusselt number. The ratio R1 represents the energy content ratio, which is also an indicator of the energy efficiency of the boiler.

8. Chemical recovery:

The green liquor cycle, the recausticizing plant and the lime cycle must operate at optimal conditions to ensure adequate white liquor availability and quality and energy efficiency of the mill. For example, a poor performance of the green liquor filters or sludge filters decreases the filterability of lime mud and increases the lime kiln dead load. This results in poor white liquor quality. Several mills have reported a deteriorated performance of green liquor filters or sludge filters/thickeners. Even when apparently solved locally, these problems tend to propagate to further process stages of the lime cycle. This causes decreased lime filterability, higher tendency for ring formation in the kiln, lower free CaO and increased dead load. In certain cases, the problems could spread affecting white liquor composition causing scale formation in the digester or in the evaporation plant. These problems are most likely caused by an accumulation of non-process elements (NPEs) in the chemical recovery cycle due to an increased mill closure. The main objective of the chemical recovery loop is to maintain a steady-state white liquor (WL) composition so that pulp quality is maintained. Unsteady WL composition implies an increased consumption of bleaching chemicals, wash-water, energy, as well as related operating costs.

Optimizing the purge of the non process elements is vital for the overall process economy of the pulp mill. As mentioned earlier, accumulation of non process elements' may lead to a series of problems, frequent problems are scale-formation on the process equipment, inefficient filtration, decomposition of oxygen-based bleaching chemicals induced by transition metals, increased energy consumption, and formation of sticky dust in the recovery boiler caused by potassium and chloride.

8.1 Slaker and causticizer:

In the slaker, lime and green liquor are mixed to produce white liquor. The slaking reaction is an exothermic reaction that reaches full conversion. However, because limestone is a naturally occurring mineral, its physical characteristics vary widely. The variation in raw material properties results in variations of quality of the calcium hydroxide, the end product. The slaker is fed with lime and green liquor at a lime-to-water ratio varying between 1 to 3.3 and 1 to 5, depending on the quality of CaO. Typically, a slaker is comprised of two chambers. The first is the slaking chamber where lime and water are mixed. It is equipped with an agitator. The second chamber is usually used as a grit removal chamber. The lime slurry flows by gravity (g) from the first chamber to the grit chamber. The viscosity of the slurry is reduced by the addition of cold water to allow the heavier grit to settle to the bottom of the second chamber where the grit is elevated and discharged by a screw. The slaker is equipped with a sedimentation type classification device to remove unreacted lime and grit from the system as shown in figure 5-4.

The most important factors affecting the slaking efficiency are given in table 5-7. The influencing parameters include the torque which represents the power of agitation (τ), the design parameters of the equipment (height and diameter), the characteristics of the solids-liquid mixture (densities, diameter of particles, solubility) and the operating conditions (velocity, retention time). The slaker is assumed to be perfectly mixed and at steady state.

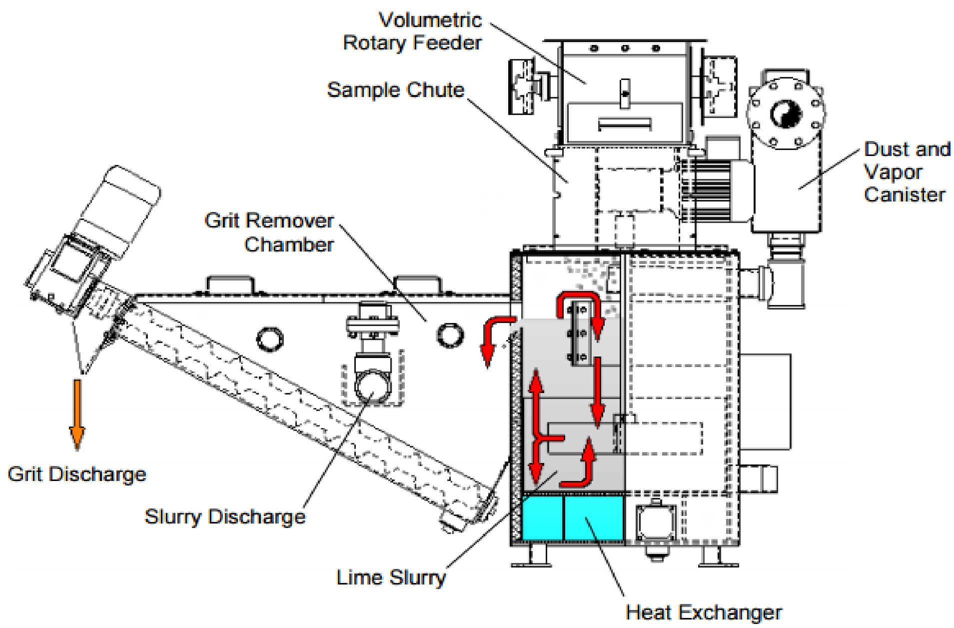

Figure 5-4 : Typical slaker flow pattern [58]

Table 5-7: Parameters characterising the Slaking

Parameters	***Description***	***Units***	***Dimensions***
τ	Torque (F*r)	$Kg*m^2/s^2$	ML2T-2
g	Gravitational force	m/s^2	LT-2
ρparticles	Density of the particles	kg/m^3	ML-3
ρliq	Density of the green liquor	kg/m^3	ML-3
A	Agitator area	m^2	L2
t	Retention time	s	T
v	Velocity in (tangential velocity)	m/s	LT-1
μ	Viscosity of green liquor	Pas	ML-1T-1
r	Radius of particles and radius of agitation palm of the stirrer	m	L
H	Height of the tank	m	L
s	Solubility	m^2/kg	L2M-1
m	Mass flow	Kg/s	MT-1

The dimensionless numbers obtained for the slaker are:

$$N1 = \frac{A}{rH} = aspect\ ratio; \quad N2 = \frac{vt}{g}; \quad N3 = \frac{t^2 g}{H}; \quad N4 = \frac{\tau}{mvH}; \tag{10a}$$

$$N5 = s\rho H; \quad N6 = \frac{s\mu}{v}; \quad N7 = \frac{tv}{H}; \quad N8 = \frac{\rho v d}{\mu} = Re$$

$$R1 = \frac{\rho}{\rho}; \quad R2 = \frac{m_{lime}}{m_{water}}; \tag{10b}$$

The dimensionless groups obtained relate the properties of the mixture to operating conditions and design characteristics. The dimensionless numbers N1 and N8 have explicit physical meaning: the former is the aspect ratio of the chambers and the latter is the Reynolds number that gives an indication of the type of flow as function of the operating conditions. The number N2 represents the tangential forces over the gravitational forces. This number should be fixed in order to have an adequate horizontal flow and grit removal rate (≤1). Similarly, N3 and N7 give an indication of the horizontal flow in the slaker as a function of its dimensions. The numbers N4, N5 and N6 combine properties of the mixture (solubility and viscosity) and operating condition (power of agitation and velocity). The dimensionless KPIs should be maintained constant for constant operating conditions (τ, v). Optimum operating conditions should however be determined. While the hydrolysis of quick lime is an exothermic fast reaction, the causticizing reaction is an equilibrium reaction and therefore reversible. It never actually reaches full conversion. This reaction takes time and thus, typically 4 agitated tanks called causticizers are installed in series. The causticizers have the same dimensionless numbers as the slaker. The residence time should be closely monitored and controlled in both the slaker and the causticizers: it indirectly determines the amount of grit removed as a function of the diameters and settling rate of the particles, and of the amount of white liquor produced.

8.2 Clarifier:

Clarifiers are settling tanks equipped with mechanical implements for continuous removal of solids being deposited by sedimentation. Clarifiers are generally used to remove solid particulates (known as sludge) that settle at the bottom of the tank [40]. There are two clarifiers in the chemical recovery loop. The first one is the green liquor clarifier that eliminates the insoluble components in the smelt and non-process elements. The second is the white liquor clarifier that eliminates the grits and unreacted lime mud. The critical parameters involved in the clarification are given in table 5-8. The governing parameters include the velocity of inlet and outlet flows as well as the dissolved solids collected at the bottom of the clarifier, and all the operating parameters and design characteristics (height and diameter).

Table 5-8: Parameters characterising the Clarifier

Parameters	***Description***	***Units***	***Dimensions***
$m_{solids\ in}$	Mass flow of solids in	kg/s	MT-1
$m_{solids\ in\ overflow}$	Mass flow of solids in the overflow	kg/s	MT-1
$m_{solids\ in\ underflow}$	Mass flow of solids in the underflow	kg/s	MT-1
$m_{overflow}$	Mass flow of overflow	kg/s	MT-1
$m_{underflow}$	Mass flow of underflow	kg/s	MT-1
t	Retention time	s	T
D	Diameter of clarifier	m	L
H	Height of the clarifier	m	L
ρ_{liq}	Density of clarification liquor	kg/m^3	ML-3
$\rho_{particles}$	Density of particles	kg/m^3	ML-3
g	Gravitational force	m/s^2	LT-2
v_l	Velocity of liquor in	m/s	LT-1
v_p	Velocity of particles settling	m/s	LT-1

The dimensionless numbers obtained are:

$$N1 = \frac{H}{D}; \qquad N2 = \frac{gt}{v_p}; \tag{11a}$$

$$N3 = \frac{vt}{H}; \qquad N4 = \frac{mt}{\rho H D^2}; \;\; ; \qquad N5 = \frac{(m_{solidsIn} - m_{solids\ in\ Overflow})}{m_{solidsIn}};$$

The dimensionless number N5 is the most important KPI for the clarifier as it represents the ultimate performance of solids removal in the clarifier. The other dimensionless KPIs should be maintained constant for the optimum operating rate that maximizes the value of N8. N1 is the dimensionless physical aspect ratio and N2 and N3 give an indication on the rate of settlement of particles.

8.3 Dregs filter:

Dregs removal is a key unit operation in the liquor cycle; its function is to control the buildup of non process elements. As mentioned earlier, fluctuations of this buildup are felt throughout the pulping liquor recovery cycle. Also, some NPEs are soluble in green liquor (GL) but less so in white liquor (WL) [40]. Hence if they are not removed from the GL, they can accumulate in the lime mud circuit thus lowering lime availability and increasing kiln fuel cost. Good performance of dregs filter is essential for the overall operation of the process.

The critical parameters involved in the filtering phenomena are given in table 5-9. The influencing parameters include the bed permeability, the cake resistance, the pressure increase through the filter membrane, as well as the retention time and properties of the filtrated liquid.

Table 5-9: Parameters characterising the Dregs filter

Parameters	***Description***	***Units***	***Dimensions***
k	Bed permeability	%	NA
R	Cake resistance/(1/thickness of cake)	m^{-1}	L-1
ΔP	Pressure difference	Pa	ML-1T-2
A	Filtration area	m^2	L2
Q	Filtration volume	m^3/s	L3T-1
v	Velocity	m/s	LT-1
t	Retention time	s	T
g	Gravitational Force	m/s^2	LT-2
h	Height	m	L
ρ	Density of filtration liquor	kg/m^3	ML-3
μ	Viscosity of liquor	Pas	ML-1T-1

The dimensionless numbers obtained are:

$$N1 = \frac{h^2}{A} \; or \; \frac{h}{R}; \qquad N2 = \frac{v}{tg}; \qquad N3 = \frac{vt}{h}; \tag{12a}$$

$$N4 = \frac{\Delta P}{g\rho h}; \qquad \mathrm{N5} = \frac{\Delta P t}{\mu} \;; \qquad N6 = \frac{\mu d}{Q\rho}$$

The dimensionless number N1 is the design ratio of the equipment, and the numbers N2 and N3 give an indication on the direction of the flow, whether it is horizontal if the tangential velocity is too high or vertical if the retention time or the velocity are too low. The remaining numbers N4, N5 and N6 give an indication on the flow resistance during the filtration. The resistance is either caused by pressure difference increase or by viscosity increase.

8.4 Lime kiln

The calcium carbonate is heated in a rotary or vertical kiln to drive away CO_2 from limestone ($CaCO_3$) and produce calcium oxide (or quick lime) CaO by calcination. Calcination conditions highly affect the quality of the quicklime produced. The following factors are the major determinants of the quality of CaO: purity of limestone, temperature of kiln during calcination, resident time in the kiln and concentration of CO_2 in the kiln atmosphere. The particles size of the limestone fed must be relatively uniform (particle diameter) to achieve even heating. Since the temperature in the kiln and the residence time are constant, the heat penetration in the particles of limestone would be affected by size variability. Heat does not quite penetrate to the core of larger size stones, therefore, the center of these pieces remain as calcium carbonate while the outside is converted to CaO. For medium size stones, the heat penetration is complete and therefore the conversion is also complete. For smaller stones the outside layer is overheated forming a hard outer shell where water cannot penetrate, therefore the slaking process is greatly retarded or even prevented. The critical parameters involved in the slaking are given in table 5-10; the most important ones are the design and operating conditions of the equipment and the properties and the lime stone.

Table 5-10: Parameters characterising the Lime Kiln

Parameters	***Description***	***Units***	***Dimensions***
dp	Particles diameters	m	L
Cp	Heat Capacity	kJ/kg/K	QM-1Ɵ-1
LHV	Low Heating Value of fuel	kJ/kg	QM-1
T	Operating temperature	K	Ɵ
m	mass flow	kg/s	MT-1
D	Kiln diameter	m	L
t	retention time	s	T
v	velocity	m/s	LT-1
ss	Specific surface	m^2/kg	L2M-1
L	Length of kiln	m	L
g	Gravitational Force	m/s^2	ML-2

The dimensionless numbers obtained are:

$$N1 = \frac{mss}{vL}; \quad N2 = \frac{LHV}{T*Cp(CaCO3)}; \quad N3 = \frac{vt}{L\ ord}; \quad N4 = \frac{v}{gt}; \tag{13a}$$

$$N5 = \frac{gL}{v^2};$$

They describe the performance of calcination reactions and give information on the flow inside the kiln. The number N1 is the specific surface area of lime stone fed to the kiln as a function of its characteristic length and tangential velocity. It must be monitored with the temperature along the lime kiln. The number N2 is the ratio of the energy liberated during combustion of natural gas to the energy required to heat the calcium carbonate to the desired temperature for the production of lime. Numbers N3, N4 and N5 give an indication on the flow direction inside the lime kiln.

These numbers should be controlled in regards with the diameter of the calcium carbonate (lime mud) particles, and the flow rate (or velocity). The velocity increases when smaller diameter particles are fed and decreases when in the opposite case. To achieve optimum calcination reaction, the velocity, the temperature along the lime kiln and the dimensions of particles of lime mud should be evaluated simultaneously, using the above dimensionless numbers.

5.7 Conclusion

The characterization of key-equipment of a Kraft process combined with an in-depth dimensional analysis leads to the formulation of dimensionless numbers that can be used as performance indicators. Dimensional analysis is a valuable tool to describe physico-chemical phenomena that take place in unit operations and to formulate dimensionless equations that best describe their performances. The dimensionless KPIs developed in this work take into consideration the operating conditions, the design parameters and the fundamental physical parameters involved in each unit operation. The optimum operating ranges must be determined for each KPI in order to monitor the performance of individual equipment. Real time monitoring of KPIs will help mill personnel by providing them with several approaches to control the system performance and operation fluctuations and to reduce their energy consumption. However, additional instrumentation may be necessary for the mill to be able to compute all the dimensionless KPIs.

The application of some of the developed dimensionless numbers is presented in Part II of this paper. Not all dimensionless KPIs could be used however to evaluate the performance, because of the lack of instrumentation and measurement required in the pulp mill analysis in Part II.

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CHAPTER 6. ARTICLE 4: EQUIPMENT PERFORMANCE ANALYSIS OF A CANADIAN KRAFT MILL. PART II: DIAGRNOSTICS AND IDENTIFICATION OF IMPROVEMENT PROJECTS

6.1 Presentation of the article

This paper has been submitted to the Chemical Engineering Research and Design in two parts. The development of new dimensionless key performance indicators (KPIs) based on a dimensional analysis of Kraft process equipment is presented in Part I. The equipment performance analysis of an operating Kraft mill, by means of key performance indicators (KPIs) is presented in Part II.

6.2 Abstract

The Kraft process is an intensive user of capital, energy, water, and chemicals, and is particularly vulnerable in the present precarious economic situation. Therefore, Canadian Kraft pulp mills offer good potential for improvement, especially if the equipment and unit operations are diagnosed in details by means of specific Key Performance Indicators (KPI). The characterization and performance analysis of equipment is a prerequisite to optimization. A thorough evaluation of the equipment performance must be performed to assess the actual vs. the expected performance before proceeding to any kind of energy improvement project. A systematic methodology for equipment performance evaluation through key performance indicators (KPIs) is presented in Part I. New key performance indicators (KPIs) based on dimensional analysis as well as other conventional key performance indicators are used to efficiently analyze and diagnose the causes of inefficiencies of the equipment, and propose adequate remedial actions. The methodology has been applied to an Eastern Canadian Kraft mill and several improvement projects leading to 30% of energy savings are proposed, entailing a reasonably low investment cost and a payback of 1.1 a.

Keywords: Kraft process, equipment performance analysis, dimensionless key performance indicators, energy efficiency, systems performance.

6.3 Introduction

The Canadian pulp and paper industry has been going through a difficult phase for the last decades because of many reasons, the emergence of new competitors from emerging countries, the reduction of paper demand, the increase of energy prices, and the strict environmental regulations [1,2,3,4]. The pulp and paper industry is among the largest industrial consumers of energy and water, and is forced to increase its energy efficiency to face the precarious economical situation [2]. As a result, a variety of methodologies and technologies has been developed to address the energy efficiency challenges and has produced significant energy savings [3]. However, these energy savings often imply high capital costs for major modifications in the plant, and are difficult to justify by mill management [5]. Major capital investment are often required when several causes are combined, for instance, when improvement to product quality and increase in production rate are sought simultaneously [5]. However, cost-effective improvement projects are possible through proper process performance and efficiency evaluations [6].

Conventional optimization or energy enhancement methodologies such as Pinch analysis, do not address process issues, such as whether wash stages could be operated with less water. They are applied with the assumption that all equipment and unit operations are working efficiently or as intended, which is not always the case in operating pulp and paper mills. Hence, results need to be considered in the light of in-depth process knowledge, and equipment performance evaluation. This is especially the case for the aging Canadian Kraft mills [2]. Older equipment often uses more water, chemicals or energy than necessary. Such equipment may also present a bottleneck to future production increase [5]. Thus, a structured equipment performance evaluation is a pre-requisite step to any energy optimization procedure and implementation projects, to avoid unnecessary commitment of expenditures in the long term.

Evaluating the individual equipment and unit operations of a mill will help channelling efforts to address points of concern in an efficient manner, and understanding fundamental mechanisms of process systems will lead to an easier identification of inefficiencies [7]. This type of equipment performance analysis can lead to low capital costs projects generating gains in the long term [6].

Low capital cost solutions begin with careful housekeeping; close monitoring and efficient operating equipment [5].

One tool that is mentioned in the literature for process performance evaluation, is the comparison of energy, water and electricity consumption of a mill with the Canadian average and best practice mills, using key performance indicators [2]. This comparison leads to a preliminary appraisal and identification of inefficient departments in the mill. Calculating and comparing key performance indicators of a mill with a Canadian average was reported to be helpful in identifying general inefficiencies [8]. Further analysis is however required to pinpoint the exact location and unit operations of inefficiencies.

Lang and Gerry [9] proposed indicators to monitor process control systems and identify periods where control loops are outside the normal mode or when they oscillate. These indicators identify areas with significant deviations from target points (energy or material consumption) but do not provide information on what is causing these deviations. Similarly, Buckbee [10] defined indicators as the ratio between the setpoint and the actual targets achieved. The challenges that are associated with wide variations in energy savings led the industries to an intensive monitoring. Van Gorp *et al.* [11] proposed a strategic method for utility distribution and energy management based on metrics for energy consumption per unit of production. The metrics are compared to the goals set for the energy reduction projects and a mathematical relationship is used to monitor the consumption compared to the targets. Retsina [12] proposed a similar methodology by adding a real-time monitoring of these indicators. Sivill *et al.* [13] proposed the use of performance indicators that take into consideration the logistic and productivity time periods of the mill based on their business strategy. Retsina *et al.* [14] developed a software to control various processes indicators. Sivill *et al.* [13] proposed the use of an indicator that connects paper production, economic parameters and the energy consumption for the overall performance evaluation of the mill. However, no work has been published on a complete structured and systematic approach for equipment performance analysis of a Kraft pulp process, by means of key performance indicators (KPIs).

The objective of this work is to present the application of a structured and systematic equipment performance analysis to an Eastern Canadian Kraft pulp mill, in order to assess the current performance of the process unit operations, identify areas of inefficiencies, diagnose the causes of inefficiencies, and propose low cost improvement projects. The work is presented in two parts. Part I described the development of new key performance indicators based on dimensional analysis of the specific Kraft process key equipment, and the current paper, Part II, presents the application of the equipment performance analysis using key performance indicators (KPIs). It should be mentioned that not all the dimensionless KPIs developed in Part I have been used in the current study, because some of them required the computation of variables for which measurements are not performed in the mill. However, a sufficient number of KPIs were used for a complete equipment performance analysis of the Kraft pulp mill.

6.4 Case study

The study is based on an operating Eastern Canadian pulp mill manufacturing newsprint [15] [11] paper using a mixture of ground pulp (60%) and Kraft pulp (40%) from softwood biomass. Only the Kraft pulping plant of the mill was simulated and evaluated in this study. Due to the large variations in instrumentation level of the various sections of the plant linked to their construction period, the measurements of the mechanical pulping plant, necessary for the construction of the process simulation, were lacking. A prorated fraction of steam and water consumption by the paper machine was therefore used in the performance evaluation to account for the extra pulp fed to the paper machine and coming from the mechanical part of the mill. CADSIM Plus® software (Aurel Systems Inc) was used for the simulation of the Kraft process of the mill. CADSIM Plus is a commercially available chemical engineering software that has been widely used in the pulp and paper sector to simulate process models. The process simulation was built with the purpose of obtaining a reliable representation of a long term average steady-state of the mill, as data source for performance evaluations, and to assess the impact of the improvement projects on the overall performance of the process.

The average pulp production rate of the Kraft plant is 280 adt[12]/d. The core of the Kraft process was built in the 1930's but process upgrades were implemented later, the last major modification

[11] Newsprint is a type of paper weighting between 40g/m2 and 57g/m2 generally used in newspapers.

[12] Adt: air dry ton o pulp

being the addition of a paper machine in the 1990's. A simple schematic of the Kraft process is given in figure 6-1.

The Kraft process is the worldwide prevalent pulp manufacturing process [16] by which a wide spectrum of finished or semi-fished paper products is made. It consists of two main parts: a pulp line and a chemical recovery loop. The pulp line is composed of four main departments; the digesting department where lignin is separated from the cellulosic fibers (pulp) under the action of the delignification agent (white liquor), a solution of sodium hydroxide (NaOH) and sodium sulfide (Na_2S), the washing department where lignin is removed from the pulp, the bleaching department where the remaining lignin and dissolved solids are removed from the pulp, and the paper making department where the pulp is drained, pressed, and thermally dried to produce the final product (bleached paper).

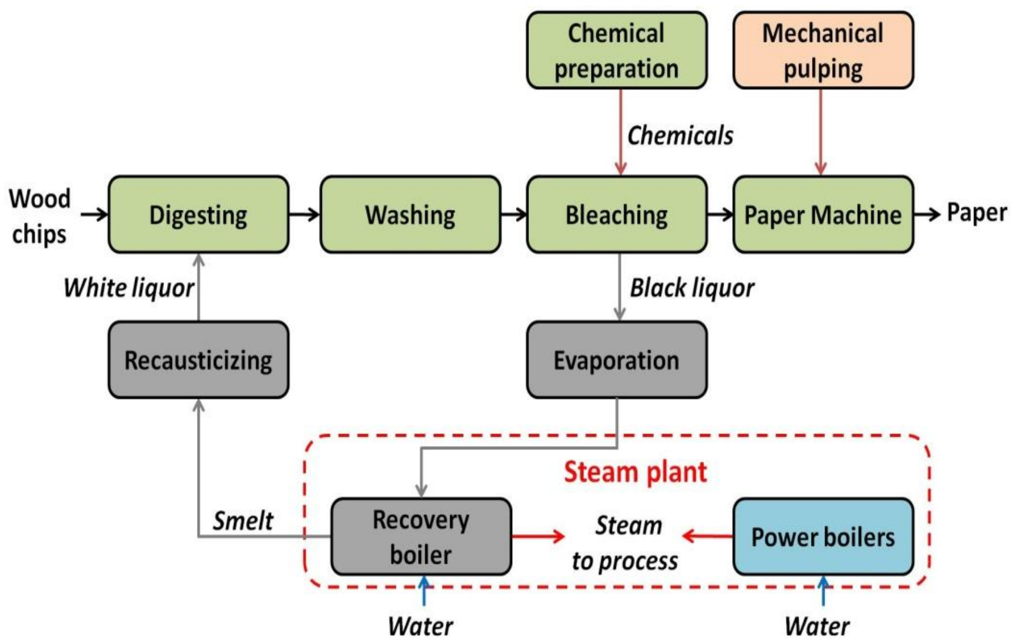

Figure 6-1: Simplified diagram of the Kraft pulp mill

The chemical recovery loop consists of three main departments: the evaporation plant where the spent delignification liquor (black liquor) separated from the fibers in the washing step is concentrated in the multi-effect evaporator, the power plant where the concentrated black liquor is burnt in the recovery boiler to produce the steam required for the process and to recover the spent chemicals, and finally the recausticizing where the spent inorganic chemicals are regenerated to produce the white liquor, through a series of chemical reactions.

The Kraft mill consumes about 110 MW of steam, 1400 m^3/h (96 m^3/adt) of water and produces 1760 m^3/h (108 m^3/adt) of effluents (the effluents amount is higher than the water consumption because of the condensation of injected steam). The aggregate steam requirement of the mill is supplied by the recovery boiler and four additional power boilers (i.e. completely supported by the recovery boiler): one is fired with bark and three with natural gas (NG). The digesting, the evaporation and the paper making departments are the largest steam consumers, and the washing department is the largest water consumer. It should be noted that a well-managed Kraft mill could be in principle energetically self-sufficient. The utilization of fossil fuel for steam production in the process is a sign of poor energetic performance. Fossil fuel should only be used to absorb the fluctuations of pulp production and seasonal variations of the steam demand (10% higher average on winter conditions). However, since the current mill is a combined Kraft and mechanical pulp, the lignin generated from the Kraft pulp is not sufficient to produce the steam required by the entire mill, and in particular to cover the full paper machine steam demand, in which Kraft and mechanical pulp are blended, and which consumes 40% of the total mill steam consumption (as a standalone Kraft mill, the paper machine consumes about 7% of the total steam requirement). The assessment of the performance of the individual equipment is an appropriate means to determine and plan the improvement modifications, and the replacement of inefficient equipment. The improvement projects with the largest gain and that entail lower investment costs are prioritized.

6.5 Methodology

The overall methodology for equipment performance analysis is schematically presented in figure 6-2. It consists of four main steps: identification of the unit operations with poor performance, diagnosis of the causes of inefficiencies, proposal of improvement projects, and economic evaluation of the proposed projects. The procedure pinpoints areas of inefficiencies and highlights issues that should be examined to formulate improvements of the overall system's performance.

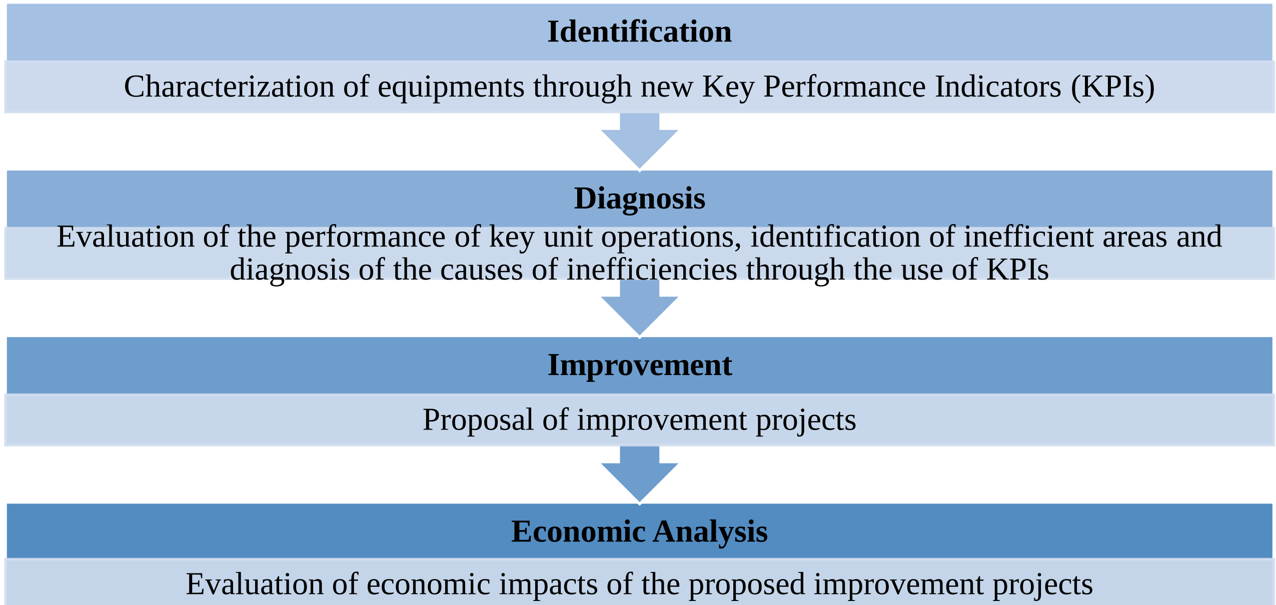

Figure 6-2 : Overall methodology for equipment performance analysis

Step 1: Identification

The identification of process inefficiencies is done by means of key performance indicators (KPIs). The KPIs used in this study are focused on water, chemicals, and energy utilisation in the process unit operations. Old or inefficient equipment generally consumes more resources (water, energy and chemicals) than necessary [5]. Therefore, the utilisation of KPIs is a privileged first step for a performance evaluation. Every department in the mill is characterized by its energy (thermal energy consumption (TEC)) and water consumption (WC) normalized to the overall pulp production of the mill. These two general key performance indicators help to situate the plant against similar North American Kraft pulp manufacturing mills. Each department is also assessed and evaluated with other key performance indicators specifically adapted to its major equipment. Dimensionless KPIs have been developed and presented in Part I of this work. The key performance indicators used in this study are presented in the table 6-1.

Digesting:

The digesting department comprises four main pieces of equipment: the steaming vessel, two heat exchangers, and the cooking vessel (digester). Steam is used in the steaming vessel to preheat the wood chips prior to the cooking vessel, and in the two heat exchangers to heat the cooking liquor extracted from the digester as shown in figure 6-3.

Table 6-1: List of KPIs per equipment and department

Department	**Process**	**Key performance indicators (KPIs)**	**References to Part I**
Digesting	• Steaming Vessel • Heat Exchangers • Overall department	$KPI_1 = \frac{m_{steam}}{m_{wood}}$; $KPI_2 = \frac{Cp*\Delta T}{\rho\Delta H}$; $KPI_3 = \frac{AU}{mCp}$; $KPI_4 = \frac{mCp_{min}}{mCp_{max}}$; $KPI_5 = TEC = \frac{\Delta H_{steam-condensate}}{m_{pulp-produced}}$;	KPI_1=R1 (2b) KPI_2=N1 (2a) KPI_3=N1 (3a) KPI_4=R1 (3b)
Washing	• Overall department • Brown stock washers	$KPI_6 = WC = \frac{\sum m_{water\_Intake}}{m_{pulp}}$. *For amount of water used at the washers:* $KPI_7 = DF = \frac{m_{waterIn} - m_{waterOut}}{m_{Pulp\_stream\_In}}$; *For amount of solute removed:* $KPI_8 = DR = \frac{\Delta m_{DSpulpin/pulpout}}{\Delta m_{DS\,water/pulp}}$; $KPI_9 = EDR = (1 - DR)(DCF)(ICF) + 1$; With: $DCF = \frac{100 - C_d}{7.33 \times C_d}$; and $ICF = \frac{99}{[99 + DF + \left(\frac{100 - C_d}{C_d}\right)]}$; and $C_d = \frac{m_{pulp}}{m_{stream}}$. *For water and solute removed:* $KPI_{10} = \frac{\Delta kappa}{m_{water}/m_{pulp\,washed}}$.	KPI_{10}=R1 (4b)
Bleaching	• Bleaching stage • Overall department	$KPI_{11} = \frac{\Delta kappa}{m_{chemicals}/m_{pulp\,washed}}$. $KPI_{12} = WC = \frac{\sum m_{water\_Intake}}{m_{pulp}}$.	KPI_{11}=R1 (5a)
Evaporation	• Evaporator • Overall department	$KPI_{13} = \frac{m_{evaporated}}{m_{steam}} = Steam\ Economy$; $KPI_{14} = TEC = \frac{\Delta H_{steam-condensate}}{m_{pulp-produced}}$.	KPI_{13}=R1 (7b) KPI_{14}=N1 (3a)
Paper Making	• Dry end section of the paper machine • Overall department	$KPI_{15} = \frac{m_{steam}}{m_{evaporated}} = Steam\ Economy$; $KPI_{16} = TEC = \frac{\Delta H_{steam-condensate}}{m_{pulp-produced}}$;	KPI_{15}=R1 (6b)

Steam Plant	• Recovery boiler and power boilers	$KPI_{17} = \frac{m_{fuel}*HHV}{m_{water}*\Delta h}$; $KPI_{18} = \frac{m_{air}}{m_{fuel}}$	KPI_{17}=1/(R1 (8b) * N1 (8a)) KPI_{18}=R1 (8b)
Recausticizing	• Overall department	$KPI_{19} = TEC = \frac{\Delta H_{steam-condensate}}{m_{pulp-produced}}$.	

The dimensionless key performance indicators, KPI_1 and KPI_2, are dedicated to the steaming vessel, the largest steam consumer of the department, and depend on the heat balance around the vessel. The dimensionless KPI_3 and KPI_4 are related to the two black liquor heat exchangers, and the KPI_5 indicates the overall steam consumption of the department.

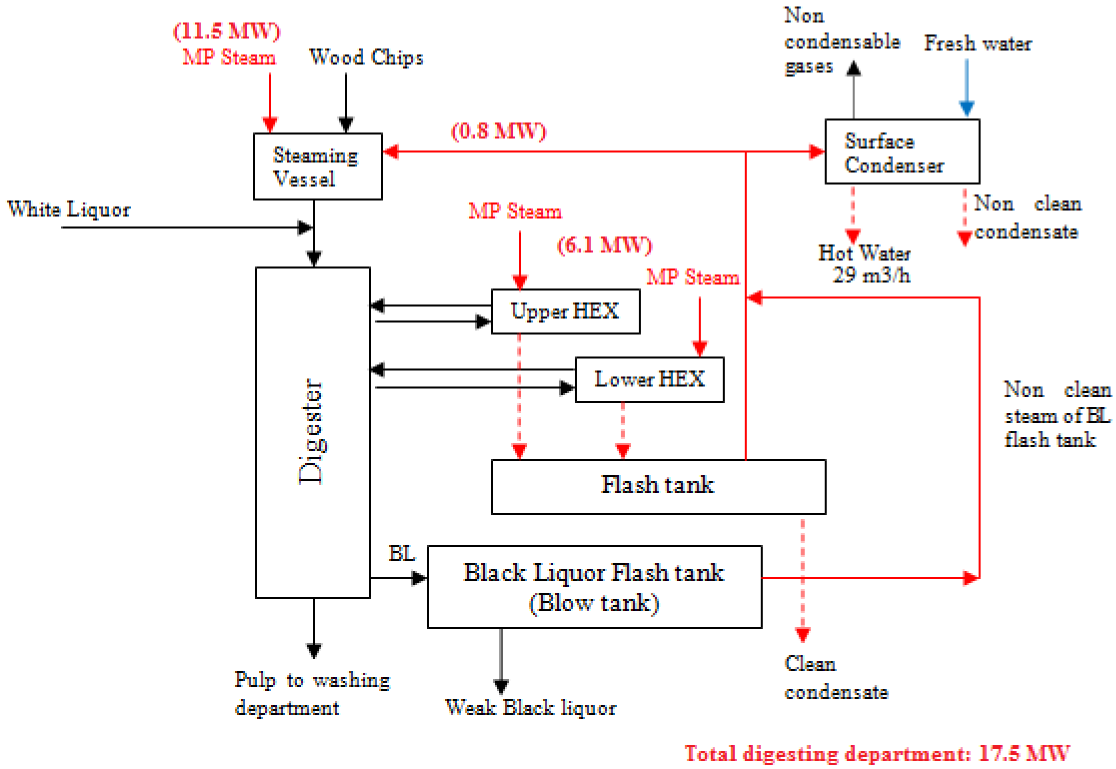

Figure 6-3: Simplified schematic of the digesting department

<u>Washing:</u>

The washing department is the largest water consumer of the mill. The performance indicator KPI_6 indicates the overall water consumption of the department (WC). The performance of the washing equipment is assessed from two angles with the use of five dimensionless key performance indicators, (i) the amount of water used (KPI_7 and KPI_{10}), and (ii) the amount of dissolved solids removed (KPI_8, KPI_9, and KPI_{10}). The KPI_7 represents the dilution factor and is a measure of the wash water applied in excess of that required for total displacement expressed as mass of water per mass of oven dry ton of pulp. The KPI_8 represents the displacement ratio at the washing equipment. Displacement washing is based on the principle of replacing by clean wash liquor the liquor which is entrapped in the pulp mat and contains a high concentration of dissolved solids. Optimum displacement (i.e. all the dissolved solids are removed) occurs when no mixing of the two fluids takes place. The displacement ratio, DR (KPI_8) is then expressed as the ratio of dissolved solids removed from the pulp to the dissolved solids concentration gradient between the pulp and the wash water. The concentration gradient is the driving force of the diffusion of dissolved solids. The ideal DR is equal to 1. In practice however, this ratio varies from 0.5 to 0.9 [17]. The KPI_9 represents the equivalent displacement ratio (EDR). EDR is a useful indicator for comparing washers of different designs and operating conditions. It compares the displacement efficiency of the actual washing equipment with a hypothetical one operating at a standard inlet consistency of 1% and outlet consistency of 12% , and having the same dilution factor (DF) [18]. It is computed by correcting the actual conditions of the washing, dilution ratio (DR) and, inlet and discharge consistencies (C_d) of the pulp (DCF and ICF from the current C_d). High EDR values for the same dilution factor imply efficient washing. Typical EDR values for the washing equipment of the studied mill are between 0.8 and 0.85 for compact baffle (CB) washers and between 0.58 and 0.78 for the rotary vacuum drum (RVD) washers [19]. The last performance indicator for the washers is KPI_{10}. It describes in a single function the amount of solutes removed expressed by the difference of Kappa[13] [20] number of the pulps entering and leaving the equipment, and the amount of wash water per pulp used in the equipment. This number is set according to mill target for the final Kappa number of the pulp produced.

Bleaching:

The bleaching department is also a significant water consuming process step. The washing stages between the bleaching towers consume large amounts of water to remove the remaining lignin,

[13] Kappa number of a pulp is a measure of the residual lignin content (or indirectly the brightness) of the wood pulp by a standardised analysis method.

the impurities, and the bleaching chemicals from the pulp. The department is assessed for overall water consumption with the use of KPI_{12}. The key performance indicators for the washing equipment in the washing department are also valid for the washing equipment in the bleaching department. Moreover, KPI_{11}, which represents the ultimate difference in Kappa number of the pulp entering and leaving the bleaching stage normalised to the amount of chemicals consumed per unit of pulp.

Evaporation:

The evaporation effect is assessed by means of two main key performance indicators, KPI_{13} which represents the steam economy (amount of evaporated water to amount of steam consumed) and, KPI_{14} which represents the overall thermal consumption of the department. The higher the steam economy per number of effects, the more efficient is the evaporation department. The typical value of steam economy for a six-effect system is 5.5 (kg/kg) [20].

Paper Making:

The paper making department is a large steam consumer of the mill. Steam is consumed in the dry end section of the paper machine. The performance of this section is assessed by the use of KPI_{15} which represents the steam economy. It is important to note that unlike the evaporation department, the steam economy in the paper machine has the inverse definition, the amount of steam consumed per evaporated water. Hence, the lower this value is, the better is the efficiency of the equipment. A typical value of kg steam per kg water evaporated for a modern well-maintained paper machine is 1.3 [20]. The KPI_{16} represents the overall steam consumption of the department normalised to its pulp production.

Steam Plant:

The steam plant is composed of the recovery boiler and four power boilers. Three power boilers are fired with natural gas, and one is fired with bark. The power boilers and the recovery boiler efficiencies are assessed with KPI_{17} and KPI_{18}. The KPI_{17} represents the thermal efficiency per fuel consumed, and the KPI_{18} represents the air-to-fuel ratio. The latter should be lower for the power boilers fired with natural gas. However, this ratio must be closely monitored in all cases, and maintained constant at a value as low as possible (higher than 1).

Recausticizing:

The recausticizing department is assessed with KPI_{19} characterizing the overall thermal consumption of the department. However, modern and well managed mills (that have a good energy management strategy) have zero steam consumption in this department [21].

Step 2: Diagnosis

The KPIs are calculated for each unit operation and compared to target set points. KPIs far from their target values are symptomatic of inefficiency. The inefficiencies are possibly due to poor operating conditions, poor heating transfer due to equipment corrosion or fouling, or old equipment that needs to be partly or completely replaced.

Step 3: Performance improvement

Performance improvements derived from the diagnostics made. They are identified based on the KPIs values and on published work, best available techniques, and good engineering practice guidelines [5, 8, 22]. The projects include modifications of operating conditions, improvement of maintenance, or replacement of parts of or totality of the equipment concerned.

Step 4: Economic analysis

Changes in the operating conditions and maintenance improvements entail investment costs and may also increase the operating cost of the process. The capital cost requirement is computed by analogy to published work, and proportionally adjusted for the identified and proposed remedial projects.

The following assumptions are considered for the economic evaluation.

- The natural gas price is \$3/GJ. The HHV[14] of natural gas (HHV_{NG}) is 54.7 MJ/kg or 46.25 MJ/m^3[23].
- The price of fresh water is 0.065 \$/m^3 [24].
- The price of effluent treatment is 0.069 \$/m^3.
- Number of operating days is 354 or 8500 hours per year [25].

[14] HHV: High heating value is equal to the heat released upon combustion of a fuel and determined by bringing all the products of combustion back to the original pre-combustion temperature and pressure, and by condensing any vapor produced

6.6 Results

Digesting:

The overall thermal energy consumption of the digesting department (KPI_5) is at the Canadian 75th percentile level (3.8 GJ/adt) which suggests the possibility of improvement and potential for significant gains. The steaming vessel and the heat exchangers are the two steam users of the department. The KPI_1 and KPI_2 are dedicated to the steaming vessel. The former describes the ratio of steam to wood and the latter represents the thermal efficiency performance of the equipment. The results of KPIs indicate an overconsumption of steam in the steaming vessel and a poor heating efficiency. This implies a potential insulation problem, which explains the high overall thermal consumption of the department (KPI_5), as indicated in table 6-2.

Table 6-2: Results of the KPIs for the digesting department

	Steaming vessel	Overall department
KPI_1 (kg/kg)	0.3	-
KPI_1-target (kg/kg)	0.04	-
KPI_2 ((kJ/kg)/(kJ/kg))	0.05	-
KPI_2-target((kJ/kg)/(kJ/kg))	0.06	-
KPI_5 (GJ/adt)	-	3.8
KPI_5-target (GJ/adt)	-	2.2

On the other hand, the KPI_3 and KPI_4, dedicated to the two heat exchangers, indicate that the latter are operating efficiently.

The steam consumption in the steaming vessel could be lowered if proper improvements and good insulation to the equipment are provided. Live steam should not be injected into the steaming vessel (figure 6-3), and recycled steam from the blowdown black liquor flash tank should suffice for the heating required by the wood chips temperature gradient of, based on the heat balance. This can result in 11.5 MW of total steam savings, which account for 10% of the total steam consumption of the mill. The impact of the heat loss reduction in the equipment has been assessed using a simulation model on CADSIM Plus. By improving the maintenance of the steaming vessel, the steam injection could be avoided, and consequently, the quantity of mixture of non-condensable gases and flashed steam will be reduced. This would result in a reduction of 6 m^3/h of hot water at 80^oC from the surface condenser of the digester department. The capital investment to improve the steaming vessel equipment and new piping to return the clean condensate to the steam plant is approximately 0.1 [26] and 0.25 M$, respectively. The energy savings and revenue generated take into account the increase of operating cost due to the heating of water to compensate for the decrease of condensates from steam injection.

Washing:

The washing department is an intensive consumer of water and has a direct effect on the steam consumption in the evaporators [27], and on the chemical consumption in the bleaching department. Thus, the efficiency of washing is important for these two subsequent processes. Reducing water consumption induces energy savings from the evaporation, but could imply an increase of costly bleaching chemicals consumption. The performance of the washing department is mainly represented by the amount of wash water used, and the amount of solute removed from the pulp. The 5 five dimensionless KPIs are given in table 6-1. The washing department case-study mill consists of a deknotter, two compact baffle washers (CB washers), a screener, and two thickeners (rotary vacuum drum RVD Washers). The pulp leaving the deknotter that removes the uncooked pulp and sends it back to the digesting is first washed in two CB washers. The washers are placed in series to achieve higher removal efficiency. The rinsed pulp is screened to remove oversize particles, and washed and thickened again in two vacuum drum washers. The washed and thickened pulp is then sent to the bleaching department. The four washers receive fresh water from the warm water tanks in order to maximize the concentration gradient and enhance the removal of solute. The deknotter and screeners receive filtrates from the filtrate tank of the washers. The washers and filtrate tanks in the washing department consume 44% of the total warm, hot, and fresh water of the mill. The KPI_6 which represents the overall water consumption of the department indicates a high amount of water consumption in the department compared to an average North American bleached Kraft mill (96 m3/adt vs. 90 m3/adt for an average 1980' bleached Kraft mill) [28]. Table 6-3 presents the results of three performance indicators for the washing equipment.

Table 6-3: Results of the KPIs for the washers

	KPI_7 (DF)	KPI_8 (DR)	KPI_9 (EDR)	Typical EDR
CB Washer 1	1.3	0.92	0.81	0.8-0.85
CB Washer 2	1.31	0.81	0.71	0.8-0.85
RVD Washer 3	6.76	0.82	0.86	0.58-0.78
RVD Washer 4	6.76	0.82	0.86	0.58-0.78

It should be mentioned that the mill produces very high quality and clean pulp with dissolved solids content in the outlet stream from the last washer below 0.04%. However, there are still possibilities to further reduce water usage. The EDR for the second CB washer is below the typical value but the dilution factor in the two last washers is extremely high (typical DF is around 2.5). The distribution of water wash between the four washers could be improved. The water throughout could be increased in the first two washers and reduced in the last two, while maintaining the same inlet and outlet discharge consistency. The washing performance could be maintained while reducing the water consumption by increasing the wash water temperature and the washing rotation speed, equipment permitting. For the two types of washing equipment, wash water temperature should be maintained below 80 ˚C [29].The current wash water temperature is 52 ˚C. A slight temperature increase to 60˚C will significantly decrease the amount of wash water required to perform the same washing efficiency [29]. Thus, the total water savings possible for these washers is 66 m^3/h (15% reduction of the current consumption of the department and 6% of the total mill water consumption), provided that the brightness of the pulp exiting the department is maintained. The energy balance for this improvement project remains unchanged. The energy required to increase the wash water temperature by 8 ˚C is compensated by the energy content of the wash water saved (4 MW).

Bleaching:

For the bleaching department that consists of three stages: D_0, Eop, and D_1. The main KPIs involved describe the cleanliness of the pulp and the wash water consumption. Both of these KPIs indicate that the mill bleaching department is operating efficiently. This is expected because the profitability of the mill is strongly related to the proper use of costly bleaching chemicals. However, the overall water consumption in the bleaching department could be reduced if retention time in the washers is extended by a few seconds, and the heat content of the effluents from the washing and bleaching departments might be used installing an energy upgrading system such as an absorption heat pump.

Paper Making:

The paper machine, consumes 41.5 MW (5.15 GJ/odt[15]) of steam to pre-heat the air, to warm up the white water at the silo chest, and to dry the paper sheets. The equipment accounts for 40% of total steam consumption of the mill. The dryer alone consumes 24.0 MW of this steam which is 22% of steam consumption of the mill. The computed steam economy for the dryer is 1.1 ton of steam consumed per ton of water evaporated. This amount is smaller than the typical steam economy of 1.3 t/t [30], so the paper machine is operating efficiently, a result that could be expected because it is the newest equipment installed in the mill and represents the best available technology in pulp machinery in North America.

Evaporation:

The analysis of 6 effect train evaporators that concentrate the weak black liquor (WBL) from 19 to 50 % dissolved solids results in an overall steam economy of 5.75 tons of evaporated water per ton of steam consumed which is larger than the typical steam economy (5.5 t/t). Thus, it is reasonable to conclude that the evaporation effect is operating efficiently.

Steam Plant:

The steam plant is a key department as it generates the steam required to operate the mill. It comprises one recovery boiler, one bark boiler (PB#1), and three natural gas power boilers (PB #2, PB#3, and PB#6). Four power boilers are required to supply the steam demand of the mill because the organics content of the black liquor is not sufficient to produce steam for the entire facility. A reason is that the paper machine which treats the mixed Kraft and mechanical pulps and accounts for 40% of the total steam consumption of the mill. The analysis of the key performance indicators for the boilers, shown in table 6-4, indicates that the fuel consumption to steam generation ratios in the recovery boiler and in the two natural gas boilers (PB#2 and PB#6) are close to the 75th Canadian percentile of 1.67 (GJ/GJ) [2], whereas modern power boilers have a fuel consumption at 1.2 (GJ/GJ). The air to fuel ratio indicates that there is about 10 to 20% of

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[15] Odt: Oven dry ton of pulp

excess air in the recovery boiler and power boilers. These KPIs indicate that the recovery boiler and two power boilers (PB #1 and PB # 2) do not operate efficiently and savings opportunities are possible by implementing improvement projects. The power boilers #3 and #6 are the most efficient units in the steam plant.

Table 6-4: Results of the KPIs for the steam plant

	T (℃) air In	**T (℃) stack**	**Steam Production (MW)**	**KPI $_{17}$**	**KPI $_{18}$**
Recovery Boiler	169	478	40.1	2.17	1.2
Power Boiler 1	210	321	15.8	1.53	1.2
Power Boiler 2	172	233	15	1.6	1.1
Power Boiler 3	172	145	27.7	1.15	1.1
Power Boiler 6	210	135	18.1	1.2	1.1

The low efficiency of the recovery boiler and power boilers #1 and #2 can be detected by their low steam production and elevated temperatures of the stack gases. This low performance may be caused by several factors. It could be due to poor operating conditions (low air inlet temperature which is the case or high excess air), and to poor performing equipment. There are many sources that could compromise the efficiency of the boilers: low flame temperature due to high percentage of excess air or low inlet air temperature, heat losses to the environment due to poor insulation, and poor heat transfer due to boiler deposit formation that increase the heat transfer resistance. Blowdown water is also a source of inefficiency since its energy content that represents 3 MW of energy lost is not exploited. Upgrading modifications in the recovery boiler and in power boiler #1 are highly recommended. The possible enhancement projects could be, improved insulation of the boilers, replacement of the burners and the heat exchangers, heat recovery from stack gases to preheat the inlet air, improved process control to reduce excess air from 20 to 15%, heat recovery of the blowdown water by sending it to the warm water tank, repair of steam leakage and monitoring of the steam traps, to prevent venting a significant amount of steam. The implementation of these modifications could increase the steam production of the recovery boiler by 15 MW (37%), and 5 MW (33%) in the power boiler by [26]. However, they entail a capital cost of approximately 2.7 M$.

Recausticizing:

The recausticizing department should not be a steam user department. By adequate control of the green liquor temperature in the dissolving smelt, for instance by raising the temperature of the dilution water to the dissolving smelt from 22 to 42 ˚C, the steam consumption in the heat exchanger could be avoided, saving 1.0 MW of steam. This project entails enhanced process control and the installation of measurement devices, estimated at 0.15 M$ [22].

Summary of Results:

Several improvement projects have been proposed for the digesting, the washing, and the recausticizing departments as well as for the steam plant. The improvement of some unit operations may increase the consumption somewhere else in the mill. Therefore, to avoid problem displacement, all proposed projects have been integrated to the simulation model to assess their overall impact on the system performance.

The total increase in steam production at the boilers is 20 MW and the steam savings in the process is close to 15 MW. Therefore, the total excess steam production capacity created is 35 MW; this corresponds to 30% of the current steam consumption at the mill. The fresh water saved and the reduced effluent volumes are 66 m^3/h and 105 m^3/h respectively. These values correspond to 5% of current water consumption and 6% of the total effluent production.

The excess steam of 35 MW can be used to eliminate the use of fossil fuel (natural gas) at two power boilers, therefore, the power boilers PB #2 and PB #6 can be completely shut down reducing the steam production by 32.1 MW. The steam generation by PB #6 can be reduced by 3 MW.

Table 6-5 shows the economic analysis of the improvement projects proposed. The total capital investment cost for the performance improvement projects is approximately 3.2 M$. The operating costs would also increase by 0.2 M$/a. The net profit of 2.8 M$/a is significant, and the payback period is short (0.9 a). The natural gas savings at the boilers result in a 1.3 kt/a CO_2 emission reduction, which is environmentally advantageous. Further steam and water savings could be achieved by improved process integration.

Table 6-5: Economic analysis of improvement projects

Departments	**Improvement Projects**	**Retrofit Capital Cost (k$)**	**Saving (k$/a)**	**Simple payback time (a)**
Digester	Insulation	100	448	0.8
	Condensate return	250		
Recausticizing	Process control	150	92	1.6
Steam Plant (recovery boiler and bark boiler PB#1)	Boiler Maintenance	750	2340	0.9
	Steam traps	375		
	Condensate return	250		
	Blowdown steam Recovery to deaerator	400		
	Air requirement	150		
	Optimization of equipment	500		
	Flue Gas Heat Recovery	250		
Total		**3 175**	**2 880**	**1.1**

6.7 Conclusion and recommendations

The results of the application of the proposed equipment performance analysis methodology using new key performance indicators to an Eastern Canadian Kraft mill highlight the importance of the scope of the study. Equipment performance evaluation by means of KPIs is an efficient way to identify poor efficiency equipment and cast light on potential improvements. Low investment cost improvement project arise as results of the methodology because the improvement projects involve the enhancement of inefficient equipment rather than a complete process retrofit design. Therefore, equipment performance analysis is a necessary prerequisite step to improve the overall performance and avoid unnecessary commitment of expenditures in the long run. The KPIs developed and presented in Part I of this paper could improve the proposed methodology and direct the diagnostics towards the specific reasons of inefficiencies. These KPIs would complete the methodology and more improvement projects with low to no investment cost could be identified. A close monitoring of key performance indicators should be done to maintain the process performance once the improvement projects implemented. A data base for optimum operating key performance indicators could be developed by the mill over time, and correlation between KPIs could be developed in order to better understand and describe the processes performances.

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CHAPTER 7: GENERAL DISCUSSION

Process simulation of the case study

The operating conditions of the process have been established based on several sources of information, mainly from the process simulation on Cadsim Plus platform of the Kraft mill studied, the process measurement data archived in the (PI) ProcessBook, the data acquisition system of the mill, and finally from the process diagrams and P&IDs of the mill.

The process simulation of the case study mill has been built based on trial-and-error and required a lot of effort and input from the mill engineers. However, because it has not been based on real operating reconciled data of the mill, the simulation does not fairly represent the long term average steady state of the plant and it does not reflect the real mill fluctuation. It is recommended that data reconciliation should be performed at the earliest stages of process evaluation and simulation construction.

On the other hand, the analysis of the base case process permits the identification of certain factors affecting the overall efficiency of the mill, such as the presence of power boilers in the steam plant, the overall fossil fuel consumption, the presence of cogeneration and heat upgrading systems, the presence of non isothermal mixing, the amount of effluents generated, the level of measurement instrumentation in the mill, etc.

Date Reconciliation and Gross Error Detection

The application of data reconciliation and gross error detection to an operating Kraft mill produced a reliable data set that can be used as basis for the construction of process simulation and the evaluation of the mill performance. The data set produced aims to represent fairly the long term average steady state of the process and reflects the real operating fluctuations of the mill for the chosen period of time.

Moreover, the data reconciliation of real operating data permits the identification of strongly adjusted measurements in the processes. Large adjustments in measurement variables may be a sign of over (or under) consumption of resources, poor operating performance or wrong operating conditions. The results of data reconciliation provide a mean to identify areas of deviation from targets in the mill. Therefore process inefficiencies and malfunctions can already be flagged for further investigation.

One limitation of the application of data reconciliation to an operating Kraft mill is the lack or scarcity of measured variables. Data reconciliation is feasible only if the system is observable and redundant system (positive global redundancy). This situation is rarely encountered in operating mills. Data reconciliation requires a large amount of excess data, the redundancy, to solve the complete set of modeling equations. In old pulp and paper mills, on the other hand, there are as few measurements as necessary for the daily monitoring of the mill’s energy and chemicals consumption, and pulp production and daily expenses and revenues. There are not enough measurements and they are not well distributed in the mill in order to cover the entire process and to solve the modeling equations which represent the constraints of the reconciliation problem. Generally, additional measurement devices have to be installed, to increase the process visibility, and improve the data reconciliation precision. The placement of additional measurement devices is an emerging field and algorithms on optimum placement of measurement devices are still in development.

In the current study, the lack of measurement data in the chemical recovery loop of the mill prevented the performance of data reconciliation in the department. It is highly recommended to the mill that additional measurement devices should be installed in the chemical recovery department.

Data reconciliation is a constrained weighted least squares optimization problem, where the weight factor for each measurement represents its accuracy. In most published data reconciliation procedures, the weights of the measurements are established based on the experience of the engineers that perform the reconciliation and their knowledge of the process and the measurement instrumentation. These weights, since they are based on human judgement, introduce a bias in the system during computation and may force the reconciliation to adjust certain variables more than others, as they are presumed less accurate. To avoid this human bias, in the current data reconciliation, the weights are taken as inversely proportional of the standard deviation of the error. This choice is reasonable as it gives a fair weight factor to each measurement and does not depend on a human judgement. Moreover, it does not force reconciliation to adjust certain measurements more than others, rather, the system will iterate until convergence.

On the other hand, there are some limitations and difficulties to the application of gross error detection techniques to real operating mill data.

First, the majority of gross error detection techniques are able to detect the presence of gross errors only on redundant variables. The non redundant measurements are not tested for gross errors. Therefore, a gross error could be present in the data set without being ever detected if such detection techniques are used alone. The gross errors, if present and undetected, will spread and affect the good measurements with which they are connected via energy and mass conservation laws, and could make the reconciliation inaccurate. This is why it is highly recommended to implement a gross error detection strategy that is able to detect the presence of gross errors in all measurement data set, not only the redundant ones.

Second, most gross error detection statistical techniques are based on the elimination of the measurement suspected of containing a gross error and testing the remaining data set for gross errors. The measurement whose removal results in the biggest reduction in the test statistic is suspected of gross errors. Moreover, most gross error detection techniques are not able to estimate the magnitude of the gross error. Rather than correcting the measurement by removing the gross error, they remove the measured variable suspected of containing a gross error from the data set. This solution is viable when large numbers of measurements are available. However, this is not the case in operating pulp and paper mills. Eliminating measured variables compromises the feasibility of the reconciliation procedure. Most likely, in pulp and paper mills, the observability of the process is hindered and the system becomes unobservable even if only one measurement is removed. Therefore, the practical application of such methods is complicated.

Third, gross error detection techniques available in the literature have been built and tested on process simulations where the errors are introduced in the system in designated measurements and the test identifies correctly the measurement containing a gross error. There is no published gross error detection strategy applied to a real operating pulp and paper plant.

Fourth, the gross error detection strategies available in the literature assume the presence of one gross error at a time. Therefore, they ascribe the probability of presence of gross errors entirely to one measurement, when two or more gross errors could be present. This assumption could exaggerate the magnitude of the gross error. This limitation is avoided if multiple gross error detection strategy is performed. However, multiple gross error detection techniques are complicated to perform because the number of statistical tests to compute increases exponentially depending on the number of combinations to test.

One last difficulty of the available multiple gross error detection techniques, is that they are performed based on combinations of independent variables. In operating pulp and paper mills, the variables are strongly connected, which makes the identification of independent variables complicated. An additional mathematical procedure should be incorporated to the variable classification step developed by Crowe, in order to classify the variables into dependent and independent variables. A recommendation is to examine the columns of the incidence matrix (A) of the process and to verify that they are linearly independent.

Exergy Analysis

Exergy analysis gives an accurate insight on how well energy and resources are used, managed and distributed in the process. It shows the exergy flows between processes, the interactions between processes, and how efficient unit operations are.

Exergy analysis brings to a common denominator quality and quantity of energy contents in process streams. It identifies areas where exergy is lost and destroyed and where practical savings can be achieved.

However, exergy analysis should be performed in combination with other process integration (PI) techniques such as pinch or mathematical optimization in order to propose the most efficient design. Exergy analysis identifies areas of biggest thermodynamic imperfection and energy degradation, but does not necessarily provide the best solution or alternative on the exergy recovery systems or design.

Exergy analysis, internal heat recovery integration and entropy minimization should be combined in the analysis of energy systems such as pulp and paper mills, in order to propose the thermodynamically optimum improvement projects. The entropy minimization is a new area of research in process design engineering and has gained significant interest during the last few years. Entropy minimization is complementary to the exergy analysis. They both are based on the second law of thermodynamics, and could serve in the design of optimum equipment and in the identification of optimum operating conditions.

Key performance indicators

Key performance indicators (KPIs) are widely applied in industrial processes for equipment performance evaluation. Standard KPIs have been formulated to describe process performances and optimum operating ranges have been set as targets. A deviation from set targets is a sign of poor performance. Moreover, dimensional analysis is a pertinent tool to develop dimensionless numbers that describe the performance of an operation. The dimensionless numbers obtained take into account the important design parameters and the operating conditions relevant to the operation under investigation. However, optimum operating ranges for the dimensionless numbers obtained have to be established. In the current study, not all dimensionless key performance indicators developed have been used for the equipment performance evaluation because optimum operating rages and parameters important for the computations of the KPIs were missing. The development of optimum operating ranges for the dimensionless numbers developed for the Kraft process is highly recommended and correlations between KPIs could be established. It is recommended for the mill to investigate the optimum operating ranges for the developed dimensionless KPIs.

Equipment Performance Analysis

Equipment performance analysis by means of KPIs has been shown to be an efficient way to identify poor efficiency equipment and plan improvement projects requiring low investment costs. Equipment performance evaluation could be particularly interesting prior to the implementation of an integrated biorefinery, since certain equipment need to be enhanced or modified to increase the receptor mill productivity and debottleneck certain unit operations. This methodology will help identify the most promising enhancement modifications to improve the overall performance and avoid unnecessary commitment of expenditures in the long term.

The use of adapted key performance indicators that take into account the design parameters of the equipments and the operating conditions facilitate the unit operations' performance monitoring and the diagnostic of the causes of inefficiencies. This procedure results in the identification of practical remedial solutions to improve the equipment efficiency.

Equipment performance analysis should become a standard procedure in pulp and paper mills and should be performed in a frequent basis. Real time optimization, monitoring and control of key performance indicators should be integrated in the mill energy consumption reduction strategy.

Context of the Canadian Kraft pulp mills

The application of the proposed methodology to an operating Canadian Kraft mill revealed significant savings in both energy and material. However, it is worth putting the Canadian Kraft mills in an international context. Klugman *et al.* [127] published a comparison of energy consumption in chemical pulp mills, internationally, and found that the Scandinavian mills are more efficient than the Canadian mills. However, the variation in energy use was found to be remarkably large among the Scandinavian mills, which indicates that the energy saving potential is significant. Similarly, Fracaro *et al.* [128] evaluated the energy consumption progression of the Brazilian P&P industry during 30 years by an energy decomposition analysis and an energy efficiency index approach. An international comparison based on this approach revealed that both the Swedish and Finnish mills were the most efficient, followed by the Brazilian, American and Canadian mills. Canada is the only country where there was a reduction in the energy efficiency levels from 1979 to 2009 [128]. Therefore, assuming that an average Canadian Kraft mill is less efficient than an average Scandinavian mill, it is expected that the application of the proposed methodology would reveal less significant savings than those reported in the current study. Nevertheless, it is assumed that savings are still possible in any pulp and paper because of two main reasons: the first is that most commonly, the minimum energy targets are set based on the first law of thermodynamic and the current methodology proposes more practical minimum energy consumptions and the second reason is that the current study proposes new key performance indicators that reveal in a straightforward way the causes of the inefficiencies in a process, facilitating the diagnostics. These indicators will help identify optimum operating ranges and could be used for process control and optimization, in order to decrease the mill energy and material fluctuations. An improved process control will improve the overall mill performance and energy efficiency.

Scope of application of the methodology

The methodology proposed is intended to be used by process engineers in the P&P industry and in other industries also relying on water-based processes such as the mining, metallurgy and agro-food industries, or high energy intensive industries such as petrochemical industries.

CHAPTER 8: CONCLUSION AND RECOMMENDATIONS

The main objective of this work was to develop new key performance indicators specially tailored for the Kraft process, and to quantify the performance of individual equipment for the use of energy, water and products, in order to improve the performance of the overall process.

The objective was achieved, and a systematic methodology for equipment performance analysis from a standpoint of energy, water and chemicals utilization by means of new key performance indicators (KPIs) has been developed and applied to an operating Canadian Kraft pulp mill. The stepwise methodology consists of 5 steps:

- Process simulation and application of a data reconciliation and gross error detection strategy,
- Exergy analysis,
- Equipment performance analysis by means of new KPIs,
- Synthesis and summary of improvement projects,
- Economic evaluation of the improvement projects proposed.

The development of a computer aided simulation of the process is necessary to analyse the performance of its unit operations and quantify exchanges between systems.

Data reconciliation and gross error detection strategy applied to operating Kraft mill studied produced a reliable set of data that represent the long term average steady state of the mill. The results of the application of data reconciliation identified strongly adjusted measurements, which indicate the presence of possible process inefficiencies, over/under consumption of energy and water or inadequate control of operating conditions, in certain unit operations.

Exergy analysis of the process gave a broad perspective for the detection of thermodynamic inefficiencies. The concepts of exergy destruction and losses are essential to identify areas where practical savings can be achieved, without over-estimating the practical maximum savings possible.

New dimensionless key performance indicators have been developed based on a thorough dimensional analysis of the major Kraft process equipment. However, the suggested optimum operating ranges for the developed KPIs have to be determined based on experiments.

The improvement of the process by applying the unified methodology results in substantial energy and resources savings involving low capital investment.

The consideration of all driving forces of the process gives a broader perspective of the process performance efficiency. The application of this kind of methodology should become a standard procedure and should be performed at the earliest stages of enhancement methodologies.

Original Contribution

The main contributions of this thesis are summarized as follows:

- A systematic and strategic methodology for equipment performance analysis has been developed and tested by its application to an operating Canadian Kraft mill.
- Data reconciliation and a new gross error detection strategy based on four statistical tests have been applied to an operating Canadian Kraft mill. The gross error detection strategy reveals the presence of gross errors in the redundant and the non redundant data set.
- Exergy analysis has been performed on the case study Kraft mill using new concepts of avoidable and inevitable exergy loss and destruction. These new concepts identify process thermodynamic imperfections and where practical exergy savings are possible.
- New KPIs for Kraft process unit operations have been developed based a dimensional analysis using the Buckingham Pi theorem. The proposed KPIs take into account the governing operating conditions of each unit operations and the main design parameters.

The results of this study can serve as benchmark for developing a quantified list in terms of energy savings potential and opportunities for improving the efficiency of the P&P industry. The methodology can be adapted and applied to the mining, metallurgic, agro-food or petrochemical industries.

Recommendations for Future Research

Dynamic data reconciliation could be performed based on the key performance indicators developed. Dynamic dimensional analysis for time dependent parameters could be particularly interesting to investigate unit operations that require deeper knowledge. This procedure will facilitate the real time performance monitoring and control of the mill.

Exergy analysis should be combined to other process integration procedures, either a mathematical optimization or a pinch-based methodology, to propose the most thermodynamically efficient heat exchange design networks.

Optimum operating conditions could be investigated and determined using the entropy minimizing optimization procedure.

Correlations between the dimensionless KPIs proposed could be investigated, in order to identify the most critical operating parameters that govern each unit operation, and determine the optimum operating ranges for each KPI.

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APPENDIX A – DATA RECONCILIATION

1. Data collection:

The representation of a variable in the PI ProcessBook of the mill is presented in figure A-1.

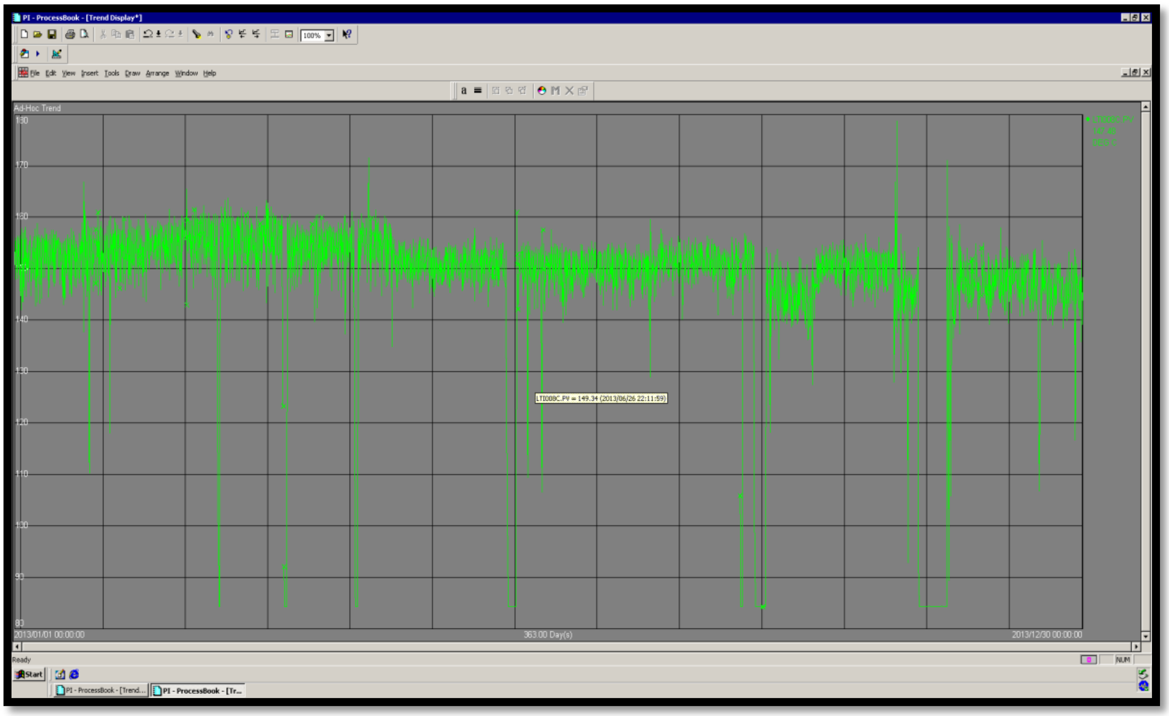

Figure A-1 : Measurement of a variable over a year

2. Variable Classification:

a. Graph theory

According to the graph theory, the process has to be represented by a graph, which can be simply derived from the flow diagram of the process, and by adding an additional node designated as the ‘’environmental node’’ and connect the input and output streams of the system to that node.

The graph theory stipulates that: an unmeasured variable is not observable, if and only if, it is part of a cycle containing only non-measured variables. As for redundant variables, they are identified by applying the following procedure:

- One begins by merging each pair of nodes connected by an unmeasured stream or variable to construct a reduced graph which contains only the measured variables. The measured variables eliminated, upon melting of the nodes are not redundant and the flow forming the reduced graph are measured and redundant variables.

b. Crowe's method: QR factorization method

The QR factorization method is as follows. Let A_u be an invertible matrix of dimension $(m \times n)$ with $m \geq n$, (using a permutation matrix to allow the inversion of a non-square matrix) and with n linearly independent columns. There exist one unique couple (Q, R) where Q is an orthogonal matrix of dimension $(m \times m)$ and R is a superior triangular matrix of dimension $(m \times n)$, and all the diagonal coefficients being positive, such as $A_u = QR$, with:

$$Q^T Q = I \qquad \text{and} \qquad R = \begin{bmatrix} R_1 \\ 0 \end{bmatrix} \tag{A-1}$$

R_1 is an upper triangular matrix of dimension $(n \times n)$.

0 is a matrix full of zeros of dimension $((m-n) \times n)$

I is an identity matrix

The factorisation of A_u could be performed using the following Matlab command:

[Q , R] = qr (A_u).

The matrix Q, obtained after the factorisation of A_u, could be divided by Q_1 of dimension $(m \times n)$ and Q_2 de dimension $(m \times m\text{-}n)$. A_u could be written as:

$$A_u = [Q_1 \quad Q_2] \begin{bmatrix} R_1 \\ 0 \end{bmatrix} \tag{A-2}$$

If both sides of the equation are multiplied by Q_2^T the following equation is obtained:

$$Q_2^T A_u = Q_2^T [Q_1 \quad Q_2] \begin{bmatrix} R_1 \\ 0 \end{bmatrix} \tag{A-3}$$

With Q an orthogonal matrix:

$$Q_2^T \,[Q_1 \quad Q_2] \begin{bmatrix} R_1 \\ 0 \end{bmatrix} = [0 \quad I] \begin{bmatrix} R_1 \\ 0 \end{bmatrix} = 0 \qquad \text{(A-4)}$$

Consequently :

$$Q_2^T\, A = 0 \qquad \text{(A-5)}$$

A non redundant variable represents a column of the reduced matrix ($Q_2{}^T A_u$) where all its elements are nil, and an observable variable is a variable represented by a row in the R_1^{-1} matrix where all its elements are nil.

From the previous equation (equation A-5), one can conclude that the desired projection matrix is Q_2^T :

$$P = Q_2^T \qquad \text{(A-6)}$$

3. Data reconciliation :

a. Linear system with all variables measured

The least square minimisation can be written as follows:

$$\min_x \; (y - x)^T \;\; W^{-1} \,(y - x) \qquad \text{(A-7)}$$

with

$$y - x = e \qquad \text{(A-8)}$$

Thus, $$\min_{x} e^T \ V^{-1} e \qquad \text{(A-9)}$$

The Lagrange multipliers' method permits to solve the optimization problem under constraints. The Lagrange multipliers can be written as:

$$L = \ e^T \ W^{-1} e - \lambda \, A(y - e) \qquad \text{(A-10)}$$

With A the incidence matrix, and W the variances matrix of errors:

The problem becomes:

$$\min_{x} L \qquad \text{(A-11)}$$

To minimize L,

$$\frac{\partial L}{\partial e} = 0 \qquad \text{(A-12)}$$

$$\frac{\partial L}{\partial \lambda} = 0 \qquad \text{(A-13)}$$

Consequently:

$$\frac{\partial L}{\partial e} = 2 \ \ W^{-1} e + 2 \, A^T \lambda = 0 \qquad \text{(A-14)}$$

$$\frac{\partial L}{\partial \lambda} = -2\,A\,(y - e) = 0 \tag{A-15}$$

Thus:

$$\text{e} = -\,A^{\,T}\,\lambda\,W \tag{A-16}$$

$$\lambda = \; -A\,y\,(A\,A^{T}\,W\,)^{-1} \tag{A-17}$$

The analytical solution to the reconciliation problem using the Lagrange multipliers (by replacing λ)

$$\hat{\mathrm{x}} \; = \mathrm{y} - \mathrm{W}\,\mathrm{A}^{\mathrm{T}}(\mathrm{A}\,\mathrm{W}\,\mathrm{A}^{\mathrm{T}}\,)^{-1}\;\mathrm{A}\,\mathrm{y} \tag{A-18}$$

b. Successive linerization

The general principle of the successive linearization technique is to linearize the nonlinear constraints using a Taylor expansion of the first order around the estimated values of the variables. Applying the Taylor expansion, the resulting linearized problem may be written as follows:

$$\mathrm{A}_{\mathrm{x}}\;\mathrm{x} + \mathrm{A}_{\mathrm{u}}\;\mathrm{u} = \mathrm{b} \tag{A-19}$$

With x and u the measured and the non measured variables respectively, and A_x and A_u are the Jacobian matrices of the measured and the non measured variables, respectively. These matrices are obtained by partially deriving the constraints of the system:

$$A_x = \frac{\partial f}{\partial x} |_{x_i, u_i} \qquad \text{(A-20)}$$

$$A_u = \frac{\partial f}{\partial u} |_{x_i, u_i} \qquad \text{(A-21)}$$

With :

$$b = A_x \, \widehat{x_\imath} + A_u \, \widehat{u_\imath} - f\,(\widehat{x_\imath}, \widehat{u_\imath}) \qquad \text{(A-22)}$$

i represents the iteration during the successive linerization and $\widehat{x_\imath}$ et $\widehat{u_\imath}$ are the estimates for the measured and the non measured variables.

The strategy consists of eliminating the non measured variables using the QR factorization method of the matrix A_u. Consequently the problem can be written as:

$$Q_2^T A_x \, \widehat{x_\imath} = Q_2^T \, b \qquad \text{(A-23)}$$

With Q_2^T the projection matrix.

Then, the system is solved through a sequence of iterations:

$$\hat{x} = y - W\,(Q_2^T A_x)^T (Q_2^T A_x\, W\,(Q_2^T A_x)^T\,)^{-1}\,(\,Q_2^T A_x\, y - Q_2^T\, b) \qquad \text{(A-24)}$$

$$\hat{u} = R_1^{-1}\; Q_1^T\; b - R_1^{-1}\; Q_1^T\; A_x\, \hat{x} \qquad \text{(A-25)}$$

With $\widehat{x_1}$ et $\widehat{u_1}$ are the estimates for the measured and the non measured variables.

Q_1 , Q_2 , R_1 et R_2 are the matrices from the QR factorisation of A_u .

Then, a new iteration begins. The constraints function f (x,u) and the Jacobian matrices A_x and A_u are recalculated and a new estimates are evaluated. The iterations continue until convergence.

APPENDIX B – THERMAL ENERGY EFFICIENCY ANALYSIS AND ENHANCEMENT OF CANADIAN KRAFT MILLS

ABSTRACT

The implementation of the integrated forest biorefinery is a potentially effective way to diversify the product portfolio of the Canadian Pulp and Paper (P&P) industry and generate new revenues. However, it is subject to constraints and limitations. One constraint is high energy efficiency that ensures independence from fossil fuels. In order to achieve this goal a new innovative methodology for the analysis of the energy efficiency of water-based P&P processes has been developed and validated. Specific features of this methodology include combined steam and water systems analysis, a project oriented approach, and the use of heuristics rules. This report presents the results of the application of this original methodology to the energy efficiency of three operating Canadian Kraft pulp mills of different configurations: a dissolving pulp mill, a standard Kraft mill combined with a mechanical pulping line, and a twin-line standard Kraft mill. The energy efficiency enhancement programs developed by the application of this methodology could, if implemented, produce steam and water utilization reductions far superior to those obtained by the current engineering practice: a reduction of 30 to 40% for steam and 25 to 50% for water. The method has revealed large differences between the three mills in steam and water utilization. The proposed energy enhancement program would enable the mills to permanently shut down the current power boilers fired with natural gas, to support integrated biorefineries producing biofuels or other bioproducts, and to increase their production of electricity. The implementation of the efficiency enhancement programs in Kraft mills by themselves (i.e., without biorefineries) would have an attractive cost recovery period, varying from less than one year to about three years.

I. CONTEXT OF THE WORK

The Canadian forest can be an abundant source of renewable biomass provided it is managed responsibly [1]. As long as the forest feedstock is maintained and more trees are planted than harvested, its lifecycle will produce a neutral or negative carbon footprint. The forest can be, at the same time, a biomass feedstock and a carbon sink. On the other hand, when a fossil fuel is chemically transformed or combusted, the CO_2 which is released is derived from carbon which was stored millions of years ago. The impact on the atmosphere is therefore a net addition of greenhouse gases.

The three main components of wood, cellulose, lignin and hemicelluloses, can be separated and converted into biofuels and many other value-added bio-products. This process is called the forest biorefinery, in analogy to the oil refinery based on a fossil feedstock. Cellulose, lignin and hemicelluloses are also found in a large group of wild or cultivated lignocellulosic plants. However, the forest biomass should be a preferred feedstock for good reasons:

- It can be produced on marginal land and therefore does not compete with food crops for arable fields;
- The maintenance and development of the forest inventory already well mastered is the object of continuous technical and scientific developments;
- The separation and first steps of the transformation of woody biomass can be performed in existing pulp and paper (P&P) manufacturing facilities.

The P&P sector in industrially mature countries such as Canada has been facing difficult economic conditions for some time due to a decreasing demand for commodity paper products such as newsprint, the traditional mainstay of the Canadian industry, and other printing and writing grades. Simultaneously, new large and modern P&P plants have been built in tropical regions endowed with low labor costs and fast growing forests with maturation periods of 10 to 20 years versus 50 to 75 in Canada. To regain its economic prosperity, the Canadian P&P industry is implementing novel transformative technologies and developing wood biomass-derived products to penetrate new markets [2]. Biosensitive packaging materials for food products, security papers with embedded codes or nanocrystalline cellulose are examples of such products. They are essentially cellulose based, as is paper. The forest biorefinery is also an important element of this reorientation strategy receiving increasing attention from the industry. It can utilize all components of the woody biomass.

The objective of an ongoing project of the E^2D^2BF[*] Research Unit of Polytechnique Montreal that is supported by BioFuelNet, a Canadian Network of Centres of Excellence, and other granting agencies[**] is to determine the conditions for the sustainable implementation of woody biomass converting plants within, and linked to, P&P manufacturing facilities. This concept schematically represented on Figure 1.1 is called the integrated forest biorefinery. Part of a process stream rich in hemicelluloses, lignin or cellulose is diverted from the receptor P&P mill and fed to a converting plant called the biorefinery. Kraft pulping, the prevalent pulp making process worldwide has been chosen for the initial phase of the project. Work has now been initiated with other pulping processes using chemical and mechanical technologies. Also, the work has concentrated on the conversion of hemicelluloses and lignin while cellulose remains used for cellulose-based products for the time being.

Hemicelluloses are complex polymers of various sugars. They can be directly extracted and degraded into sugars such as xylose, arabinose, glucose, mannose and galactose by hydrolysis [3]. The sugars can then be transformed by chemical or biological pathways such as fermentation, into a variety of biofuels and primary chemicals which can be further processed by specialty product manufacturers. Feasible processes based on proven technologies have been designed by computer aided techniques to manufacture fuel substitutes such as ethanol and butanol [4] and chemical precursors such as furfural and xylitol [5]. An experimental program has been undertaken to develop and validate new technologies to concentrate and purify the sugar solutions by nanomembranes and to increase the yield of the fermentation steps by substrate medium enrichment with fodder extracts, and the development of new ferments [5].

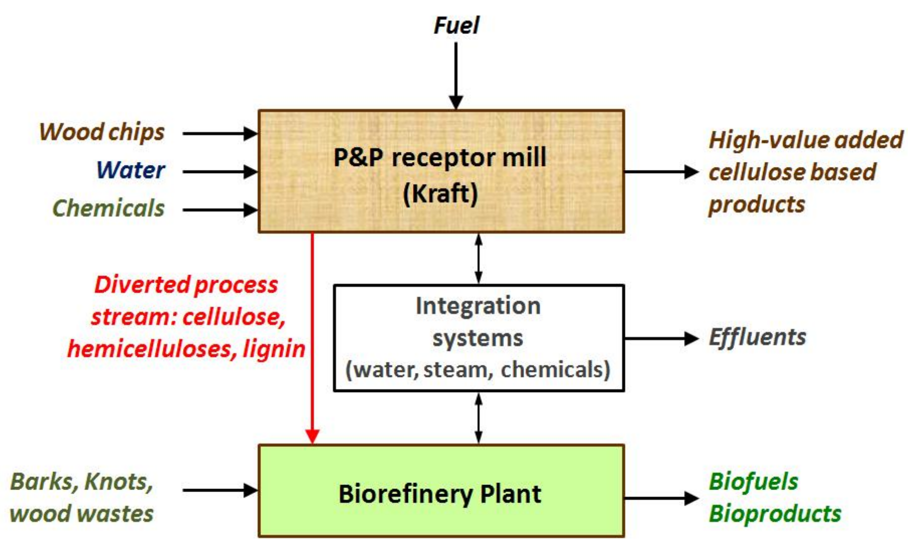

Figure 1.1: Scheme of the integrated forest biorefinery

The ***lignin*** which binds the supporting structure of wood is degraded and solubilised by a strongly alakaline solution in the first step of the Kraft process. The residual delignification liquor (black liquor) which contains the solubilised lignin is separated from the fibers which then form the pulp. The black liquor is concentrated and burnt to produce steam. Part of the lignin in the black liquor can be precipitated under acid conditions, washed, filtered and dried. This lignin can then be converted into a large number of valuable chemicals of the phenolic group. Alternately, it can be used as a fuel. A feasible process based on non proprietary technologies has been developed using computer aided techniques to support Canadian owned technologies [6]. The use of CO_2 contained in stack gases for the acidification step is being investigated and the enhancement of the lignin filterability is being studied experimentally [7]. An alternative lignin extraction process based on a combination of electrochemical technologies and membrane separation is being investigated at the laboratory scale. Preliminary results are very encouraging [8].

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[*] E^2D^2BF, French acronym for Energy Efficiency and Sustainable Implementation of the Forest Biorefinery

[**] CRNSG (INNOV-UC); CRIBIQ; MDEIE (Soutien aux initiatives internationales de R&D).

The operations of the Kraft receptor mill and biorefinery plant are highly integrated thus creating a process configuration which has very significant impacts on the overall facility [9].

- The removal of part of the hemicelluloses or lignin reduces the heat value of the black liquor which is burnt to produce steam. This can be compensated by an increase in pulp production rate thus generating additional revenues;
- The diversion of part of a process stream and return of effluents from the biorefinery alter the delicate chemical balance of the Kraft process and remedial actions must be taken;
- The increased heating and cooling demand created by the biorefinery process could lead to increased dependency of the global site on fossil fuel. To avoid this purpose defeating outcome, a new and innovative ***Methodology for thermal energy efficiency analysis and enhancement*** has been developed. A schematic of the stepwise methodology is presented in Figure 1.2.

This methodology which is an extension of a pioneering analysis by Mateos-Espejel *et al.* [10] incorporates several important innovative features which, in combination, produce synergetic effects. They include in-depth pre-evaluation of the current performance level of the process, combined steam and water systems analysis, identification of interactions between the various modes of energy production and delivery and, a project oriented approach. Some elements of the methodology are still in development [11]:

- In step 1: data reconciliation for efficient development of coherent simulation models;
- In step 2: analysis of individual unit operations and identification of off-target operating conditions by means of new energy and material performance indicators.

Nevertheless, it has been applied, in its current state of development, to three operating Canadian Kraft mills representing a spectrum of process configurations and has produced results superior to the current engineering practice. The reduction of steam consumption ranges from 30 to 50% and the corresponding reduction of water usage ranges from 25% to 50%. The additional steam and water demand created by the biorefinery plant could easily be met. The individual detailed results obtained for each mill considered are presented in this report. On the basis of these results it can be anticipated that the fractions of available lignin or hemicelluloses diverted to the biorefinery could be significantly raised from the conservative level initially utilized in this project.

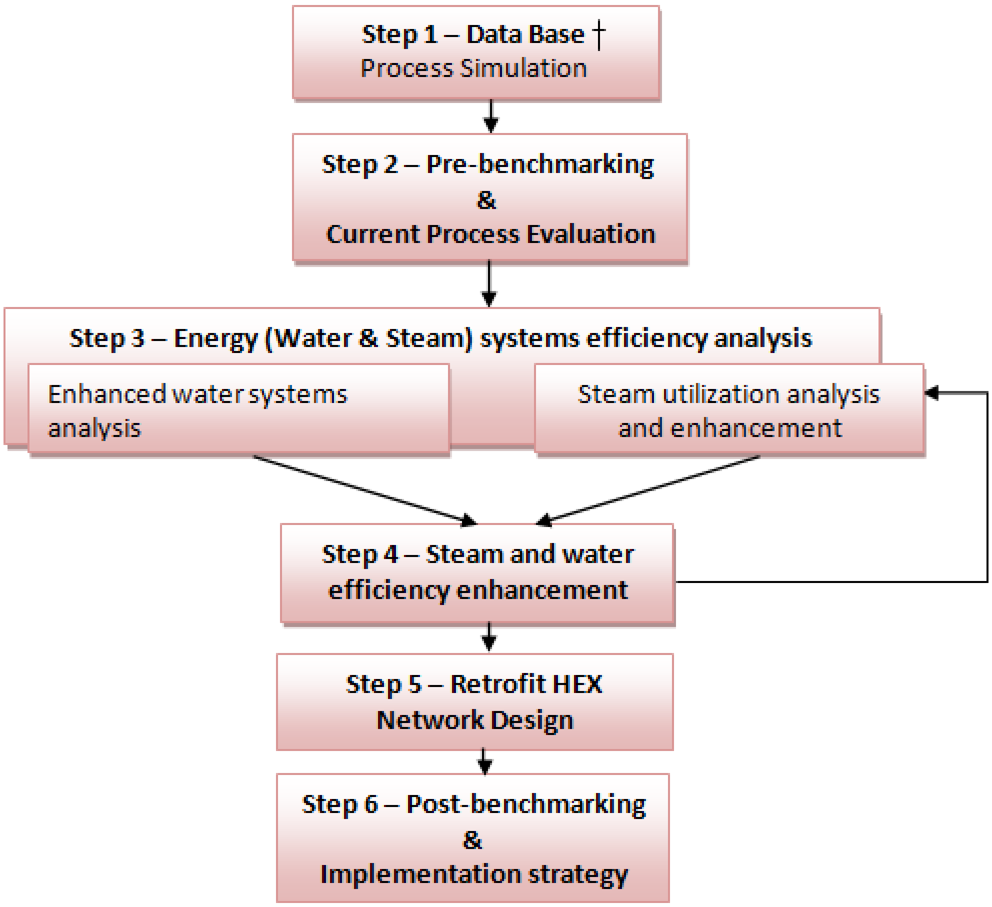


Figure 1.2: Organigram of the stepwise energy efficiency analysis

Another way to increase the rate of production of biofuels is to form clusters of integrated biorefineries with several feeder Kraft mills and a central conversion plant. A preliminary study has shown that this could be economically feasible in regions where several pulping mills are reasonably close [12].

This project incorporates fundamental principles of sustainability that include reliance on renewable sources of materials and energy and efficient use of energy [13]. The results for the three mills designated hereafter as mill A, mill B, and mill C are presented herein.

No systematic stepwise methodology has been developed to provide engineers with practical guidelines for energy and water enhancement. The present work proposes such guidelines for the application of a step by step methodology for simultaneous thermal energy and water enhancement.

II. HIGHLIGHTS OF THE ENERGY EFFICIENCY ANALYSIS

The methodology, its principles, structure and implementation have been described in Keshtkar's PhD thesis [14]. The purpose of this report is to illustrate the power and scope of the methodology by summarizing the results obtained for the three case studies. This section gives a brief survey of the methodology that is intended to help the reader understand how the results presented in sections III, IV and V were obtained. Each section can be read independently. For an in-depth understanding of the procedures and techniques utilized, the reader should consult the reference cited above.

II.1 Benchmarking (Pre- and Post-): steps 2 and 6

Benchmarking the performance of a mill consists of comparing the values of steam and water consumption and of effluent production extracted from the process simulation to published reference values. The steam consumption of the principal user equipment and of the complete mill is benchmarked against reference data from a previous PAPRICAN survey [15]. The water consumption and effluent production are benchmarked against the latest available reference data. Reference values for water consumption have been extracted from published data for typical mill designs of the 1960s and 1980s [16, 17]. Reference values for effluent production were taken from published studies of typical mill designs of the 1960s, 1980s and 1990s [18].

Benchmarking is performed twice, first in step 2 of the methodology to assess the current efficiency of the mill (Pre-benchmarking) and in step 7 to determine the improvements achieved (Post-benchmarking).

The potential steam and water savings, SS and WS, that may be achievable by the later implementation of the efficiency enhancement projects that will be developed in the course of the analysis (see section II.3) were estimated by comparing the current values to median values of the reference data used for benchmarking. They are given as a percentage of total current steam and water consumption, CS and CW, and given by the following equations; in these equations MS is the median reference steam consumption and MW the median water consumption, CSC and CWC are respectively the current steam and water consumptions of the actual mill under study.

$$SS = 100\,(CSC - MS)/CSC \qquad \text{[Eq.1]}$$

$$WS = 100\,(CWC - MW)/CWC \qquad \text{[Eq.2]}$$

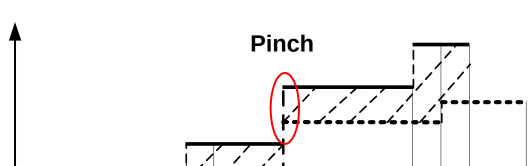
II.2 Energy (water and steam) efficiency analysis: step 3

This is the core of the methodology. It concerns the two main components of the supply and utilization of thermal energy, water and steam.

II.2.1 Enhanced water systems analysis

The Kraft pulping process is a typical water-based process; almost all streams connecting unit operations are aqueous solutions or suspensions. Two types of streams are particularly important to the water and thermal energy efficiency of a Kraft mill; (i) streams consisting of excess water borne material extracted from a unit operation and referred to as source streams and, (ii) streams supplying water or water-borne material to a unit operation designated as sink streams. A typical Kraft mill may contain 15 to 20 sources and about 25 sinks For each mill studied, an exhaustive catalogue of source and sink streams has been compiled in which each stream is defined by flow rate, concentration of dissolved solids or contaminants and temperature.

A modified water pinch analysis was used to represent the complete array of sources and sinks. Water pinch analysis [19, 20] is an extension of the well known Pinch Analysis® originally developed by Linnhoff *et al.* [21] in the 1970's. It is familiar to process engineers and has been widely applied to P&P mills [22, 23] to maximize internal heat recovery and design an optimal heat exchanger network. It is now often designated as thermal pinch analysis to distinguish the two techniques. In an analogy to thermal pinch analysis, water pinch can be represented by composite curves in which contaminant concentration plays the role of temperature (Figure 2.1). The composite curves are composed of the sources of water available in a process (water sources) and of the water demands (water sinks) by the process equipment. When the two curves are brought to pinch position, i.e., when the two stepwise curves touch, they define the optimal matching between water sources and sinks. They also show the maximum internal water recovery achievable, the minimum need for fresh water, and, the minimum water borne effluent. The potential reduction of water consumption by the implementation of this procedure is of the order of 25 to 60%. However, in this work, the dual representation of water sources and sinks by concentration and temperature was used to



appropriately reallocate sources and identify potential supplies to sinks. This procedure will be a key factor in the identification of potential energy efficiency enhancement projects in step 4.

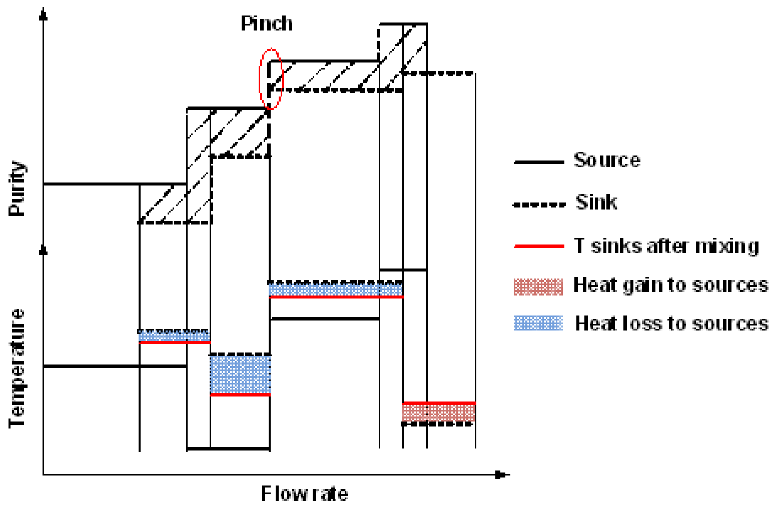


Figure 2.1: Modified water pinch diagram.

Pulp washing is a particularly critical operation from the stand point of water utilization. This operation has been analyzed in depth in a previous work [24].

II.2.2 Steam utilization analysis and enhancement

The delivery of heat by steam to a process unit can be accomplished in two ways, by condensation of the steam in a heat exchanger (steam heater) or by direct injection of steam in a process stream (direct heating). The two methods are used in a Kraft process. In order to analyze and reduce the steam utilization by the process the heaters and injection points are classified in five categories.

a. Steam heaters in which the steam cannot be replaced by another heat source because of the temperature level (e.g., digester liquor heaters);
b. Steam heaters in which the steam can be replaced by another heat source such as a process stream or hot water depending on availability (e.g., warming intake water);
c. Steam injection points that can be replaced by a heat exchanger when appropriate heat sources are available (e.g., hot water heating);
d. Steam injection points where steam consumption can be reduced by rearranging a mixed heater and steam injection system to shift the heat load from steam to water by using high temperature water from the utility system (e.g., in a bleaching stage, the steam requirement can be reduced by using water at a higher temperature);
e. Other steam injection points, i.e. those that cannot be replaced by a heat exchanger nor reduced by load shifting (e.g., steam injection in chip bin).

The implementation of the enhancement of steam utilization in each of the 5 above categories is reconsidered from three perspectives in the following order.

1. ***Alternate mode of heat delivery***. First, the way in which heat is delivered is changed whenever possible to one of the following alternatives, (i) replacing steam by another heat source, (ii) replacing steam injection by steam heaters and, (iii) adjusting temperatures;
2. ***Equipment performance adjustments***. The equipment serviced by the steam is examined to evaluate how its energy requirement can be reduced by increasing its own energy performance. This step comprises (i) computation of key performance indicators for each piece of equipment using data from the process simulation,

(ii) identifying significant deviations from target performance and, (iii) proposing remedial actions on the basis of prior experience or professional reports [25, 26];

3. ***Potential gain by heat exchanger network upgrading***. Finally, further potential energy gains by upgrading heat exchangers are estimated; however such preliminary estimations are subject to confirmation by the heat exchangers retrofit design performed later in step 5.

The overall procedure to reduce the steam consumption can visualized as a matrix as illustrated on Figure 2.2

	a. Steam heating unchanged	b. Steam heating replaced	c. Steam injection replaced by HEX	d. Steam injection reduced by load shifting	e. Steam injection unchanged
1. Mode of heat delivery					
2. Equipment performance enhancement					
3. Potential gains for HEN upgrading					

Figure 2.2: Matrix representation of the steam utilization enhancement procedure.

II.3 Identification of steam and water efficiency enhancement projects: step 4

Once the target water reallocation as well as steam and associated water requirements have been determined in the previous step, the new water and steam distribution networks are incorporated into the overall process configuration. This is done in a piecemeal fashion radiating from major equipment (e,g, digester, pulp drying machine, recovery boiler,…) or within departments (e.g. washing, bleaching, recausticising). A particular attention is given to temperature and contaminants concentrations in water streams. Heuristic rules are used to identify opportunities for networks rearrangements and integration. These rules are:

- Cascading countercurrent water flows, such as filtrates, are forbidden;
- Priority must be given to streams with high flow rates for water recycling;
- High temperature water streams must be used first;
- Mixing streams of significantly different compositions must be avoided;
- Steam injection must be replaced by steam heaters whenever it is feasible.

All the data required to support this analysis, such as temperatures, pressures, flow rates and water contaminant concentrations of water sources and sinks and steam streams are computed by process simulation using the simulation models of the mills developed on the software CADSIM Plus® in step 1 of the methodology.

About 25 to 60, enhancement projects have been generated for each mill.

II.4 Retrofit design of heat exchanger network: step 5

A new heat exchanger network is designed for each efficiency project so as to avoid excessive distances between pieces of equipment which are later connected. The enhancement projects are then integrated in the simulations of each mill and displayed department by department in a series of diagrams. A new HEX network design algorithm was developed for this work and applied to the three mills; it is illustrated in Figure 2.3.

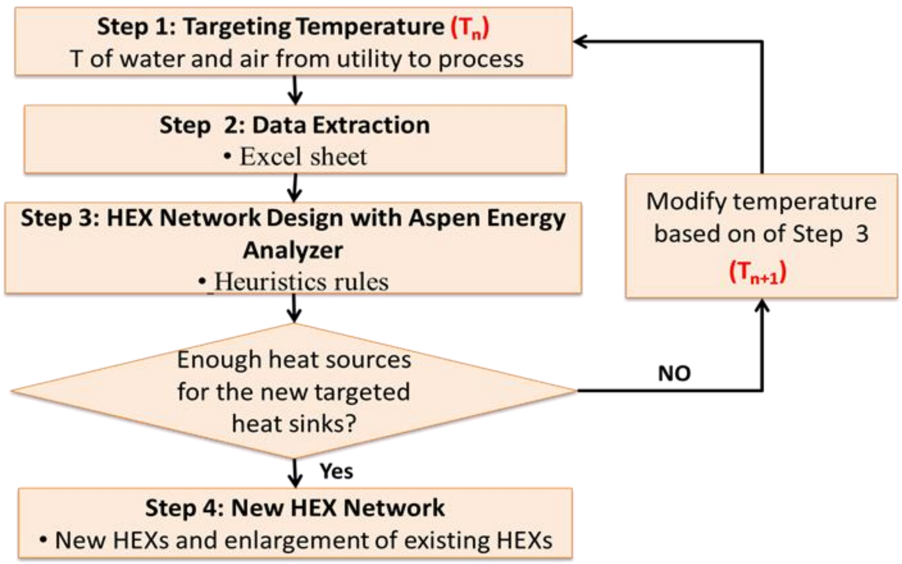


Figure 2.2: Network design algorithm

When the heat exchangers network is finalized, the steam distribution system is adjusted to its final values as it was anticipated (see sections II.2.2).

The new equipment required for the implementation of the proposed enhancement projects consists of piping (including pumps and instrumentation) and, new or modified heat exchangers. Considering that all projects cover approximately the same floor area, it was assumed that each would require 150 m of new piping including all accessory equipment. The cost of piping, CP, depends on flow rate, temperature, pressure and corrosion activity of the stream involved; For the water system of a typical pulping mill it is given by the empirical equation 3 and 4 [27].

$$CP = (734\ A + 258)\ L \qquad \text{[Eq. 3]}$$

$$A = \dot{V} / (3600 * v) \qquad \text{[Eq. 4]}$$

In these equations L is the length of the piping system (150m in this work) and A is the cross section of the pipes which is computed by equation 4 where $\dot{V}$ is the volumetric flowrate in m^3/h and v is the linear velocity of the liquid in m/s. Labor and material for insulation are assumed to represent respectively 40% and 20% of the installed cost of piping [28].

The installation cost of new or re-rated exchangers was estimated by the well known factored method [29] based on the exchange surface area. For the conditions of this mill, the purchase cost is given by equation 5 where C_B is the base cost for floating head carbon steel heat exchangers, F_D is the cost adjustment factor for fixed head exchangers, F_P is the design pressure factor and F_M the adjustment factor for 316 stainless steel. Those four factors are functions of the surface area of the heat exchanger. The installed cost of heat exchangers is given by equation 6 [30].

$$M_P = CBFDFPFM \qquad \text{[Eq. 5]}$$

$$\text{Installed cost} = 1.31\ Mp \qquad \text{[Eq. 6]}$$

The multiplying factor in repair and maintenance (2% per year) and operating supplies (0.5% per year). All costs were indexed to 2014.

II.5 Energy conversion and upgrading

The implementation of the proposed energy enhancement projects would liberate steam production capacity from the existing power plant. This excess steam capacity should be first used to reduce or eliminate the consumption of fossil fuels, a result that may produce significant operating cost reductions. When there is still a sufficient residual steam production capacity, the installation of a power generation unit is envisaged. The preliminary dimensioning and costing of heat and power cogeneration units was also performed by the factored method previously mentioned. Details of previous applications to Kraft mills can be found in [31].

There may be process or effluent streams which carry important quantities of heat that cannot be recovered by heat exchange because their temperature is too low (40 to 80 C range) but It may be technically feasible to upgrade this low energy and save cooling and heating utilities by means of an absorption heat pump. The principles of the installation of an absorption heat pump (AHP) and the judicious choice of the pump to process connections and, in particular, the way in which they must straddle the thermal pinch point have been presented in [32]. It is illustrated in Figure 2.4.

The following economic data and assumptions have been utilized to compute the profitability of the power generation and heat upgrading options.

- Reference year: 2012
- Bunker oil price: 650 $/t.
- Cost of fresh water: 0.038 $/m3
- Cost of effluent treatment: 0.10 $/m3
- Selling price of electricity to the grid : 90 $/MWhr [10]
- Selling price of steam 4$/GJ
- Number of operating days: 354 [2]
- AHP working fluid: LiBr-H_2O
- AHP coefficient of performance: 1.55

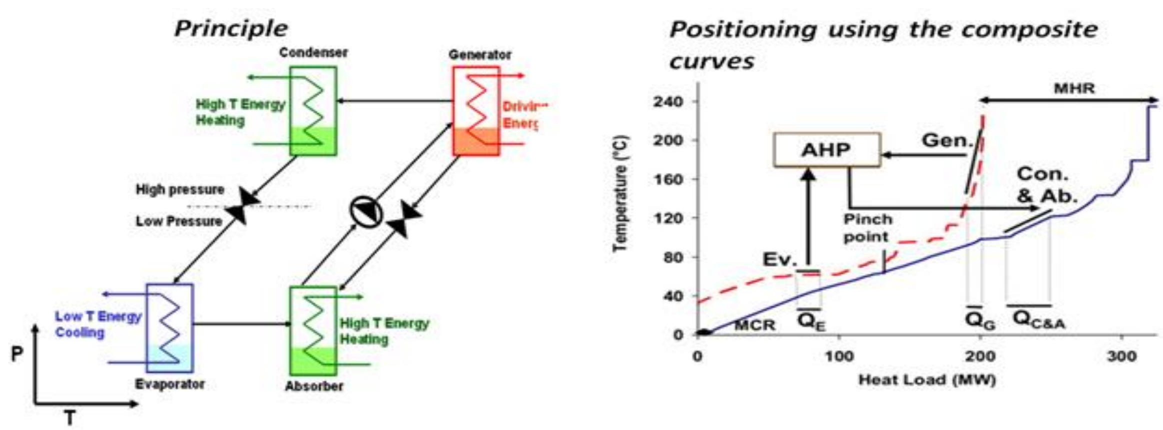


Figure 2.4: Principles of an AHP in a process

II.6 Previous Analyses of Kraft Mills

The Department of Natural Resources of Canada in collaboration with the Pulp and Paper Research Institute of Canada (now called FPInnovations) produced a benchmark for the energy consumption of North American P&P mills [15]. This reference can help a mill position itself versus its competitors and compare its energy consumption in the various parts of the process to that of similar mills. The main results of the survey are presented in table 2.1. The energy consumptions are normalized to a unit of production, the oven dried ton (odt) to facilitate the comparison. Table 2.1 gives the average energy consumption for a Kraft mill producing bleached pulp. Values were taken from 20 Canadian Kraft mills. The table highlights the large difference between the most efficient and the least efficient plants. The disparity in efficiencies shows that there is significant potential for improvement in most Canadian Kraft mills.

Table 2.1: Average energy consumption and production for bleached Kraft pulp *

	Electricity Consumption (kWh/Odt)	Fuel Consumption (kWh/Odt)	Thermal Energy Consumption (kWh/Odt)	Thermal Energy Production (kWh/Odt)	Net Thermal Energy Production (kWh/Odt)
25th Percentile	455.2	27.72	12.71	16.19	3.60
Median	550.3	32.53	16.27	18.05	1.32
75th Percentile	633.8	34.12	18.51	19.79	-0.22
Modern	370.0	NA	8.60	NA	NA

* The specific energy is determined from the sum of energies for the following areas in each Kraft mill: recausticizing, evaporators, recovery boiler and bleaching. The specific energy is the total energy divided by the bleached Kraft pulp production. The pulp production is expressed on an oven dried basis.

The American Institute of Chemical Engineers (AIChE) has also compiled data for the energy consumption of the United States P&P Industry and estimated how much energy could be saved if more efficient technologies and better practices were employed. This survey shows that the pulp and paper industry has reduced its energy consumption since 2002, primarily through the use of waste energy streams, i.e. by capturing the energy s, both air born and liquid in waste heat stream [33]. Further energy savings would still be possible by the use of best available technologies (BAT) to reach the practical minimum energy consumption.

Klugman *et al.* [34] published an international comparison of energy consumption in chemical pulp mills, and found that Scandinavian mills are more efficient than Canadian mills. However, the variation in energy use was found to be remarkably large among the Scandinavian mills themselves, which indicates that the energy saving potential is significant. Similarly, Fracaro *et al.* [35] evaluated the energy consumption progression of the Brazilian P&P industry during 30 years by an energy decomposition analysis and an energy efficiency index approach. An international comparison based on this approach revealed that both the Swedish and Finnish mills were the most efficient, followed by the Brazilian, American and Canadian mills. However, Canada is the only country where there was a reduction in the energy efficiency levels from 1979 to 2009 [35].

The improvement of energy efficiency is of paramount importance for energy intensive chemical industries such as P&P manufacturing. Improving the energy efficiency of pulp and paper mills is strongly related to the proper management of water because water is the main medium of heat transfer. This strong correlation between water and heat underlines the necessity to develop a methodology that can address the simultaneous reduction of thermal energy and water requirements. Published state of the art studies on water and energy enhancements or optimizations can be classified in 3 categories: conceptual, mathematical and combination of the two methods [36]. Mathematical optimizations consist of maximizing (in the case of energy production) or minimizing (in the case of energy or water consumption) of variables subject to a set of constraints. Conceptual methods are generally pinch-based approaches. They provide a good overview of the overall procedure by the use of powerful visualization tools.

Energy integration in the Kraft process has been widely applied, to improve overall performance and increase power generation capacity. Maréchal *et al.* [37], Douglas *et al.* [38], Parthasarathy *et al.* [39], and Freppaz *et al.* [40] investigated the use of mathematical optimization tools for energy and water allocation optimization. Goortani *et al.* [41] used a mathematical optimization method to study the impact of the implementation of a cogeneration unit along with other measures to improve the energy profile of a Kraft mill. The results of their study showed a significant improvement in energy use and the generation of a considerable surplus of energy. Savulescu *et al.* [42-44] studied the energy integration and the identification of optimal retrofit designs of heat exchanger networks. They developed a systematic method, based on the pinch analysis, to optimally design heat exchanger networks. Rafione *et al.* [45] developed a mathematical model to optimize the integration of energy and water networks in a green integrated Kraft forest biorefinery.

Many authors have developed methodologies to optimize energy and water utilization by means of conceptual approaches. Schaareman *et al.* [46] applied a combined energy and water pinch analysis to a complete mill. Both analyses were performed in sequence and iteratively. However, potential impacts were not taken into consideration to propose water reduction measures. The water and energy pinch applied to a Kraft newsprint mill producing 450,000 ton per year of newsprint, achieved savings of 60,000 tons of low pressure steam per year and 200,000 m^3/a of ground water. Koufos and Retsina [47] applied water and energy pinch independently but did not analyze the resulting thermal balance modifications. The methodology developed was applied on a deinking treatment facility and resulted in a water intake decrease of 20%. Savulescu *et al.* [48] suggested a combined energy and water analysis based on a series of charts (composite curves) in two dimensions which take into account the concentration of contaminants and the water temperature, which both depend on the water flow rates. The analysis applied to a Canadian integrated Kraft mill, specialized in white board production, resulted in an effluent reduction of 6,000 m^3/d and 37 t/h of steam savings. Mateos *et al.* [49] studied the complete process to determine the water reuse opportunities and analyze the impact on the overall thermal performance. The unified methodology for thermal efficiency improvement applied on a Canadian Kraft mill achieved 27% of steam saving and 33% of water reduction. Brown *et al.* [50] developed a method based on combined pinch analysis and optimization techniques to identify and evaluate the thermal efficiency of P&P processes. The illustration of the method by the analysis of an integrated Canadian newsprint mill resulted in an energy saving of 30 MW (22%).

A number of studies of the P&P industry have been conducted in recent years; they differ in scope and applied methodology. Axelsson *et al.* [51] investigated heat integration opportunities in average Scandinavian Kraft pulp mills using two different approaches, one conventional based on pinch analysis and the second based on process integrated evaporation. The application of these two approaches on an average Scandinavian mill revealed significant savings and created a steam surplus of more than 50 MW. Wising *et al.* [52-53] proposed a new design of secondary heat systems to replace live steam through process modifications. The new design of the secondary system proposed includes an improved removal of non process elements (NPE) in the water loops of the mill. Fleiter *et al.* [54] investigated the energy efficiency in the German pulp and paper industry and developed a model-based assessment on 17 process technologies using a techno-economic approach to identify savings potentials. They found that the most influential technologies are heat recovery and the use of innovative paper drying methods. Chen *et al.* [55] developed and proposed an energy flow analysis for the identification of improvement projects and energy savings. They found that the greatest energy saving potential lies in improving energy distribution and equipment efficiency [56].

The application of plant wide thermal and water pinch based methodologies on P&P mills showed the benefits of the conceptual methodologies. Indeed, they provide meaningful energy and water targets, identify feasible projects with real savings and give essential insights into energy and water flows distributions, benchmarks and scope. However, these conceptual approaches based on iterative and simultaneously searches for energy and water improvements may evolve into an arduous path to reach the minimum water and energy consumptions. The results may vary depending on the experience and knowledge of the person who performs the study. Simultaneous energy and water methodologies are in most cases iterative and therefore complicated and difficult to apply in practical contexts. Moreover, these methodologies may not always produce the global minimum of energy and water consumption and the results depend on how well energy and water are managed in the initial configuration of the mill.

A further barrier when developing a combined water and energy optimization is the unavailability of measured water consumption levels, which makes it difficult to target water reuse opportunities. Also, these methodologies assume implicitly that the unit operations and equipments in place operate efficiently and as intended. This is not always the case in real mills so that the optimization and enhancement results may be biased.

No systematic stepwise methodology has been developed to provide engineers with practical guidelines for energy and water enhancement. The present work proposes such guidelines by the application of a step-by-step methodology for simultaneous thermal energy and water enhancement.

III. ANALYSIS OF MILL A

Mill A produces Kraft dissolving pulp by a batch pulping process using a mixture of 65% Maple and 35% Aspen as wood feedstocks. The average pulp production rate is 750 adt/d. The core process of Mill A was built in the 1970s.

III.1 Pre-benchmarking

Figures 3.1 and 3.2 illustrate the results of the pre-benchmarking step; they show the potential steam and water consumption savings. It must be noted that since there were no published data that could be used as a reference to benchmark a Kraft dissolving pulp process at the time at which this work was undertaken, the benchmarking step was based on conventional Kraft paper pulp processes. Only Kraft processes with batch digesters were used, however, to better emulate Mill A. Also, the dissolving pulp process involves an initial treatment of the wood chips prior to digesting to extract most of the hemicelluloses from the chips by hydrolysis. Since this treatment is not included in the standard Kraft paper pulp process, this step was analyzed separately. Also, the load on the evaporators used to concentrate the black liquor is higher than in standard Kraft processes because the diluted prehydrolysate, which is reinjected at this point, brings additional water and dissolved solids to the system.

The mill departments forming the ‘’others’’ category in Figure 3.1 are the steam plant, the inlet water treatment and conditioning, and the recausticizing loop. They also include the buildings heating requirements; this non-process energy requirement has not been taken into account in the analysis and its amplitude is unknown. The total steam consumption of this category is considerably higher than the 75th percentile of Canadian mills. The steam consumption of the batch digester plant is also much higher than even the 75th percentile. This suggests that there should be significant opportunities for steam savings in mill A.

Figure 3.2 gives the water consumption for the main departments in comparison with reference data. Pulp washing, pulp drying, and chemical recausticizing consume more water than mills designed in the 1960s and 1980s. There should be significant opportunities for improvement in the water system.

The potential steam and water savings given by equations 1 and 2 are 33% and 44%, respectively.

III.2 Energy (Water and steam) efficiency analysis

III.2.1 Enhanced water systems analysis

The enhanced water pinch analysis was performed. Key results are given in Table 3.1[16]. The changes in fresh water utilization and filtrate reutilization made on the basis of water systems analysis are illustrated in Figures 3.3 to 3.5. Diagram *a* in each figure gives the current configuration of the water system and diagram *b* shows the proposed configuration. Dashed purple lines indicate the change in the flow rate of the existing connections and the dotted red lines show the new connections. There are 16 changes in existing connection flow rates and 22 new connections for filtrate reutilization would be required. The amount of total water that could be saved is 948 m^3/h or 38% of current water consumption. The total amount of sewered water sent to the effluent treatment system would decrease by 893 m^3/h or 36% of its current level.

III.2.2 Steam systems analysis and enhancement

The steam consumption of the mill by steam user type after the analysis of the steam distribution system has been performed is given in Table 3.2.

The eight steam heaters of the first group currently consume 114 MW of steam; the aggregate consumption of steam of the two paper machine dryers can be reduced by 2.6 MW by slightly adjusting the drying temperature. The operating conditions of the other 6 steam heaters cannot be changed. In the second group of steam heaters, the steam can be replaced by an internal process heat exchange in four cases (1, 4, 6, 7); the steam consumption has been

1. Tables and figures of sections III, IV and V are at the end of each section

reduced in two other heaters (2 and 3) by temperature adjustments. One steam heater remains unchanged (5). The aggregate reduction for this group of steam heaters is 35 MW. In the case of heating by steam injection, all injection points of the first group could be eliminated, thus realizing a steam savings of 11.9 MW. The steam consumption of the second group of seven injection points could be reduced by 13.6 MW and the total heat requirement could be reduced by 18.1 MW after upgrading of the exchanger network has been performed (total steam savings of 13.6 MW). An additional savings of 4.5 MW could be achieved by adjusting the temperature of the water added to the pulp line. As will often be the case, the injection points of the last group could not be rearranged nor replaced. The total steam savings that can be achieved by the implementation of the complete enhancement program is 67.5 MW (27% of current consumption).

The last two lines of Table 3.3 give the potential maximum steam savings for the complete mill. The results suggest that 11% of current steam consumption can definitely be saved and that an additional 16% of current steam consumption may be saved by upgrading the heat exchangers involved in the heat supply to the modified steam heaters of group *b*. The total consumption of the mill could then be reduced to 73% of its current value.

III.3 Identification of steam and water efficiency enhancement projects

The new process configurations derived from the results of the water and steam systems analysis are displayed in Figures 3.3 to 3.5. Table 3.4 presents a global summary of the proposed projects and the steam and water savings that ensue. The capital cost requirements are for new piping in the water network and the installation of the new or upgraded heat exchangers. The increment of operating cost linked to the operation of the additional heat exchanger area has also been estimated. The steam saving is 67.5 MW, or 27% of current steam consumption. The total water saving is 948 m^3/h or 38% of current water consumption. The 34 projects entail 25.2 M$ in capital costs and add 546 k$/a to the operating costs of the mill.

A major equipment performance improvement project must be underlined. It concerns washer #1 and is illustrated in figure 3.4. The equivalent displacement ratio (EDR) of the washer is 0.46, which is considerably smaller than the ideal value of 0.80. To improve the performance of the washer, the total filtrate should be increased from 848 to 881 t/h, which would raise the EDR to the target value of 0.8.

III.4 Retrofit design of heat exchanger network

The part of the existing heat exchangers' network affected by the retrofit operation consists of the air and black liquor (BL) preheating operations and of the warm and hot water production networks. It uses the process stream side of heat exchangers and, air and water heaters. The new heat exchanger network is displayed in Figures 3.6 and 3.7.

The network sections concerning black liquor heating, air preheating for recovery and power boilers and, the paper machine dryer are shown in Figure 3.6. The new heat exchanger network requires eight additional heat exchangers: five condensers for the new condensing turbines, one condenser for the clean flashed steam of the pulp dryer and two air economizers (one at the recovery boiler and one at the power boiler). The current air heater for buildings, pulp dryers, and recovery boiler is relocated as first condenser of the condensing turbine. The current high pressure steam air heater of the power boiler is upgraded and relocated as the second condenser for clean flashed steam of the pulp dryer. The existing cascade concentrator of black liquor is also upgraded.

The fresh water heating system is shown in Figure 3.7; it requires six additional heat exchangers two of which are available in the mill and can be upgraded (expanded exchange surface areas). The temperatures of hot and warm water have been adjusted as shown in the water utilization networks of Figures 3.3, 3.4, and 3.7b.

III. 5 Energy conversion and upgrading

Two back pressure turbines that produce medium and low pressure steam and 19.7 MW of electricity are already installed in Mill A (Figure 3.8a). In total, 257 MW of steam at different pressure levels is consumed in the process and 18.3 MW of energy is lost in turbines. The steam saved is used to reduce the bunker oil consumption by the power boiler. This leads to a reduction of 20.0 MW of high pressure steam generation. The remainder of the steam saved is 47.5 MW, which is not sufficient for exportation, hence, selling steam to the local district not advantageous. Two other options consisting of cogeneration only or combined heat and power generation to sell electricity to the grid are examined and illustrated in Figures 3.8 b and 3.8 c.

In ***Option 1*** the installation of a condensing turbine can generate 8.5 MW of extra electricity. In ***Option 2*** an absorption heat pump is installed to generate 154.3 MW of low pressure steam. The medium pressure steam (121.3 MW) discharged from the installed back pressure turbine is used to drive the heat pump by supplying heat to the generator. Low pressure steam (154.3 MW) is generated at the condenser and absorber of the heat pump of which 37.7 MW is used to drive the lowest stage of the turbine train and 116.6 MW is sent to the process. The contaminated steam, which is currently condensed in surface condensers #1 and #2, is used to drive the evaporator of the absorption heat pump. The net effect of the heat pump is to reduce steam consumption of the mill by 33 MW (13%) and reduce the load on the surface condensers. However, it does not increase electricity generation over what is already produced in Option 1 (28.2 MW). The benefit derived from the installation of the AHP is to upgrade low potential heat and produce steam. Option 1 is more attractive for this mill.

The economic aspects of both options are presented below. The total capital cost of Option 1 is 8.03 M$ to purchase a new condensing turbine with 431 k$/a of operating costs while the capital costs of cogeneration and AHP of Option 2 are 11 and 60 M$, respectively. The operating costs are approximately 2.2 M$/a. Part of the 67.5 MW of steam saved can be used to reduce bunker oil consumption by 52 t/d. The balance of steam saved can be used in the two options as described above.

The costs associated with the reduction of effluent, water consumption and bunker oil utilization and, the costs associated with electricity generation are summarized in Table 3.4. The bunker oil saving is the largest contribution to net profits in both options. Purchasing the required new heat exchanger area and condensing turbine are the main capital costs of Option 1. The capital cost of Option 2 is about three times that of Option 1 due to the purchase of the absorption heat pump, a very capital intensive piece of equipment. The payback period of Option 1 is quite short at 1.8 years. On the other hand, the payback period of Option 2 with combined heat and power and selling electricity to the grid is more than 3 times longer at 5.8 years. Therefore, with a short payback time, low capital cost and, higher net profit Option 1 is a very attractive investment.

III.6 Implementation strategy

A two-phase strategy is proposed to implement all the energy and water projects developed in this work as well as the cogeneration unit of Option 1 (Table 3.5):

Phase 1: Reduction of bunker oil consumption from power boiler: All water reutilization projects that are shown in Figures 3.3 to 3.5 as well as the network of the water production illustrated in Figure 3.7 should be implemented. These projects require 15.6 M$ of investment costs and produce a reduction of 32.8 MW of steam consumption and 12.8 M$/year in net profits with a short payback period of 1.2 years.

Phase 2: Additional electricity generation: The heat exchangers required for air preheating shown in Figure 3.6 are implemented. This produces 34.7 MW of additional steam saving that can be used to generate 8.5 MW of extra electricity by the installation of a new condensing turbine as shown in Figure 3.8 b. The extra electricity sold to the grid generates new profits of 5.8 M$/year. Implementation of this phase entails 17.6 M$ of investment for the heat exchangers and the turbine and the payback period is 3.0 years, which is much longer than phase 1. However, the combination of the two phases is very profitable.

III.7 Post benchmarking

Figure 3.1 and 3.2 illustrate the post-benchmarking results after all the proposed projects are implemented. Figure 3.1 shows that the steam consumption for pulp bleaching, and pulp drying, and other utilizations would be significantly reduced and this would bring the total steam consumption of the portion of Kraft paper pulping with batch digester lower than the 25th percentile of Canadian mills. Figure 3.2 also shows that the water consumption would be considerably reduced in the washing, bleaching, and recausticizing departments. The total water consumption would be brought close to average mills designed in the 1980s.

The potential steam and water savings computed with equations 1 and 2 on the basis of the pre-benchmarking step were 33% and 44%. The actual values based on the result of the analysis are 38% and 27%. The water savings are clearly above the initial value but the steam savings are quite short of the initial target.

Table 3.1: Mill A. Results of water pinch analysis and actual results

	Water Pinch	Actual
Pinch Point (ppm)	300	
Max. System closure (t/h)	15500	18900
Min. Fresh water (t/h)	6000	1530
Min. Effluent (t/h)	5500	1560

Table 3.2: Mill A. Steam consumption, current and after steam utilization analysis (MW)

#	Department and equipment	Current	Heat delivery	Equipment adjustment	HEN upgrading	Final[1]
	a. Steam heaters with non-replaceable heat source					
1	Digester, Cooking liquor #1	19.0	19.0	19.0	19.0	19.0
2	Digester ,Cooking liquor #2	19.0	19.0	19.0	19.0	19.0
3	Digester, Cooking liquor #3	2.5	2.5	2.5	2.5	2.5
4	Digester, Cooking liquor #4	2.4	2.4	2.4	2.4	2.4
5	Steam plant, Oil heater	3.0	3.0	3.0	3.0	3.0
6	Paper machine, Dryer #1	15.9	15.9	15.9	14.8	14.8
7	Paper machine, Dryer #2	14.5	14.5	14.5	13.0	13.0
8	Black liquor evaporators	38.1	38.1	38.1	38.1	38.1
Total a		**114.4**	**114.4**	**114.4**	**111.8**	**111.8**
	b. Steam heaters with replaceable heat source					
1	Air heater, buildings, dryers & RB	23.9	23.9	23.9	0	0
2	Recovery boiler, MP steam to air heater	8.7	8.7	8.7	0	6.2
3	Recovery boiler, HP steam to air heater	9.6	9.6	9.6	0	6.9
4	Power boiler, HP steam to air heater	3.0	3.0	3.0	0	0
5	Steam plant, Black liquor heater	9.8	9.8	9.8	0	9.8
6	Hot water heater (85oC)	1.1	0	0	0	0
7	Soft water heater (65oC)	1.7	0	0	0	0
Total b		**57.8**	**55.0**	**55.0**	**0**	**22.9**
	c. Replaceable steam injection					
1	Paper machine, Pulp filtrate tank	4.6	0	0	0	0
2	Recausticizing , Hot water tank	5.0	0	0	0	0
3	Hot water heater (71oC)	0.2	0	0	0	0
4	Hot water heater (92oC)	0.8	0	0	0	0
5	Soft water heater (65oC)	1.3	0	0	0	0
Total c		**11.9**	**0**	**0**	**0**	**0**
	d. Reducible steam injection					
1	Eop Bleaching, steam mixer	7.9	2.0	2.0	0	0
2	D1 Bleaching , steam mixer	0.9	1.2	1.2	0.8	0.8
3	E2 Bleaching, steam mixer	0.9	0.4	0.4	0	0
4	D2 Bleaching, steam mixer	3.6	1.2	1.2	0.7	0.7
5	Pulp machine , Steam mixer	0.8	0.4	0.4	0	0
6	Pulp machine ,Lazy steam shower	1.0	1.0	1.0	0.2	0.2
7	Steam Plant, Deaerator	15.0	10.3	10.3	10.3	10.3
Total d		**30.1**	**16.5**	**16.5**	**12.0**	**12.0**
	e. Other injection points					
1	Digester, Pre-hydrolysis (MP steam)	10.1	10.1	10.1	10.1	10.1
2	Digester, Pre-hydrolysis (LP steam)	16.9	16.9	16.9	16.9	16.9
3	Water treatment	0.1	0.1	0.1	0.1	0.1
4	Power	8.6	8.6	8.6	8.6	8.6
Total e		**35.7**	**35.7**	**35.7**	**35.7**	**35.7**
Grand Total (MW)		249.9	221.6	221.6	111.8	182.4
Percent of current consumption		-	89%	89%	45%	73%

Note 1: Final heat requirement after the retrofit design of the complete heat exchanger network
Abbreviations: RB: recovery boiler, MP and LP: medium and low pressure steam

Table 3.3: Mill A. Summary of steam and water savings

Step	Nb of projects	Steam savings MW	Steam savings %	Water savings m^3/h	Water savings %	Cap.cost M$	Oper.cost K$/a
Heat delivery	15	28.3	11	948	38	3.36	-
Equipments' adjustments	-	-	-	-	-	-	-
Preliminary HEN upgrading	19	39.2	20	-		21.82	546
Total	34	67.5	27%	948	38%	25.18	661

Table 3.4: Mill A. Economic comparison of alternatives 1 and 2

	Effluent Reduction (m3/h)	Water saving (m^3/h)	Excess Steam (MW)	Bunker oil saving (t/d)	Elect. generation (MW)	Effluent Reduction (M$/a)	Water saving (M$/a)
Option 1	893 (36%)	948 (38%)	67.5 (27%)	52	8.5	0.8	0.3
Option 2	893 (36%)	948 (38%)	67.5 (27%)	52	8.5	0.8	0.3

	Bunker oil saving (M$/a)	Sale extra electricity (M$/a)	Increase in oper. cost (M$/a)	Net profit (M$/a)	Total Capital cost (M$)	Payback (a)
Option 1	12.0	6.5	1.0	18.6	33.2	1.8
Option 2	12.0	6.5	2.7	16.9	97.0	5.8

Table 3.5: Mill A. Implementation Strategy of Alternative 1

Phase	Projects	Steam saving (MW)	Cap. cost (M$)	Net profit (M$/a)	Payback period (a)
1: 80% of Bunker oil savings	1-All water reutilization 2-HEXs of water network	32.8	15.6	12.8	1.2
2: Extra electricity generation	3-HEXs of air network 4-Condensing turbine	34.7	17.6	5.8	3.0
	Total	67.5	33.2	18.6	1.8

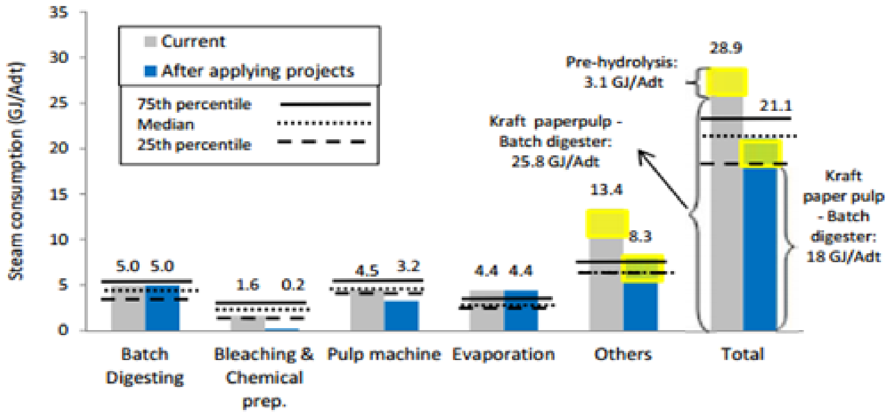


Figure 3.1: Mill A. Steam consumption of main departments and complete mill for current process configuration and after implementing performance enhancement projects

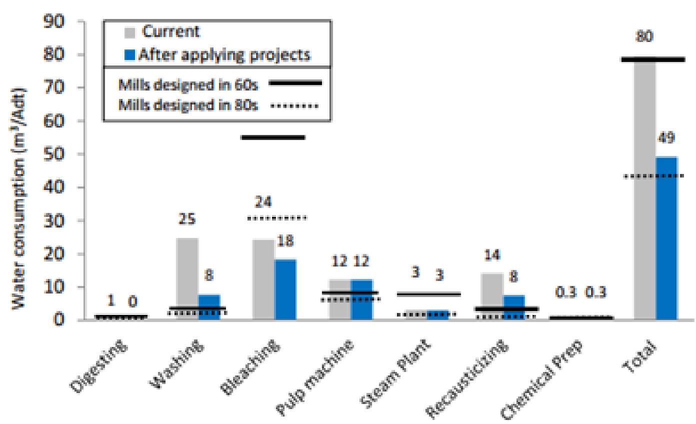


Figure 3.2: Mill A. Water consumption for current process configuration and after implementing performance enhancement projects

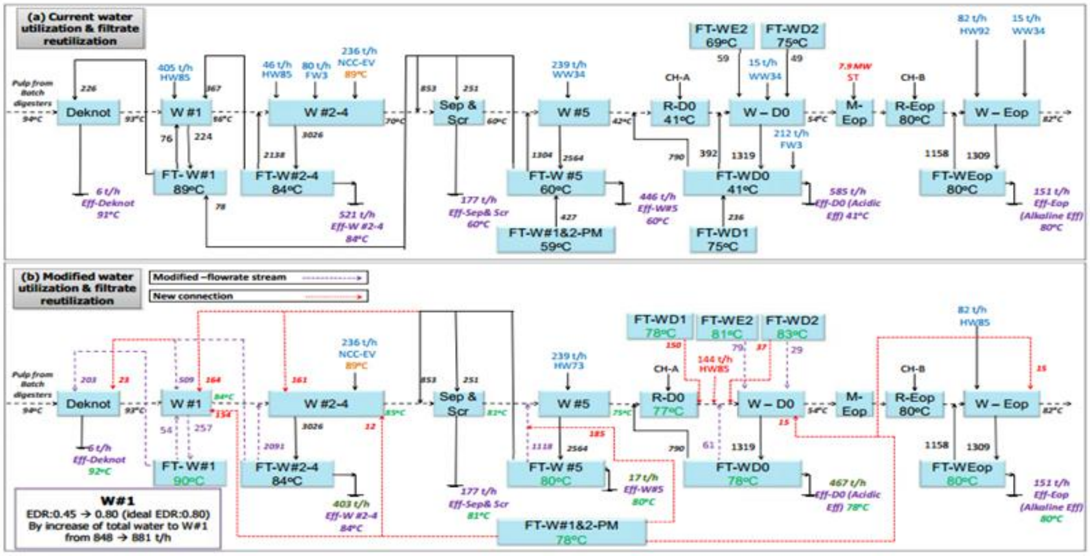


Figure 3.3: Mill A. Current (a) and final (b) water utilization and filtrate reutilization in the washing and bleaching departments.
W: washer, FT: filtrate tank, Sep & Scr.: separators and screeners, Deknot: deknotters, R: reactor, M: steam mixer, PM: pulp machine, ST, NCC-EV: non-clean condensate of evaporation, WW: warm water: FW: fresh water: HW: hot water, Eff: effluent.

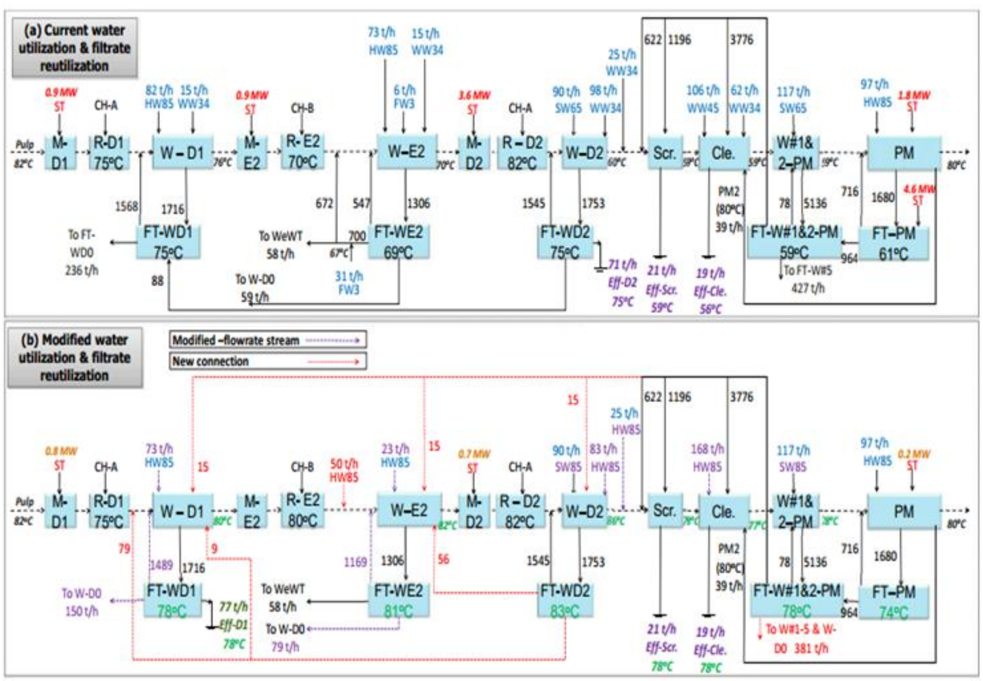


Figure 3.4: Mill A. Current (a) and final (b). Water utilization and filtrate reutilization in bleaching and pulp machine departments.
W: washer, R: reactor, M: steam mixer, FT: filtrate tank, Cle: cleaners, Scr: screeners, PM: pulp machine, Vac. P: vacuum pump, Fil: filter, WW: warm water: FW: fresh water: HW: hot water, CH-A: acidic chemicals, CH-B: base chemicals, ST:steam, Eff: effluent.

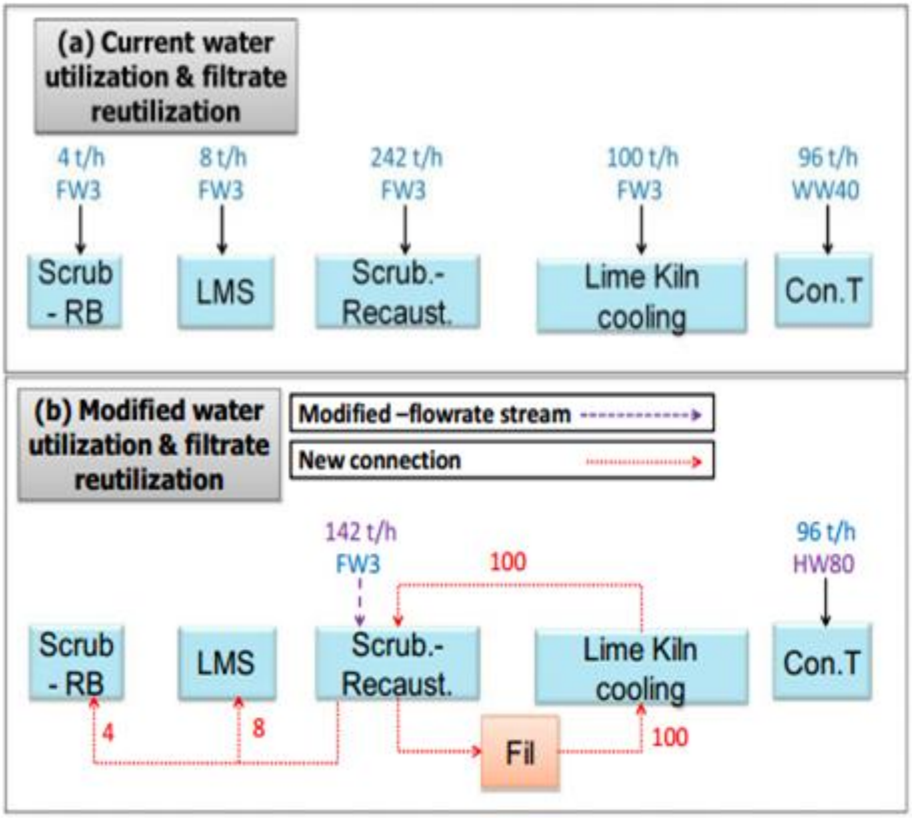


Figure 3.5: Mill A. Current (a) and final (b). Water utilization and filtrate reutilization in scrubber, recausticizing and steam plant department.

Dotted red lines are new connections; dashed purple lines are the existing connections with change in flowrate.

Scrub-RB: scrubber of recovery boiler, LMS: lime mud storage, Scrub-Recaust: Scrubber of recausticizing, Con. T: condensate tank, Fil: filter.

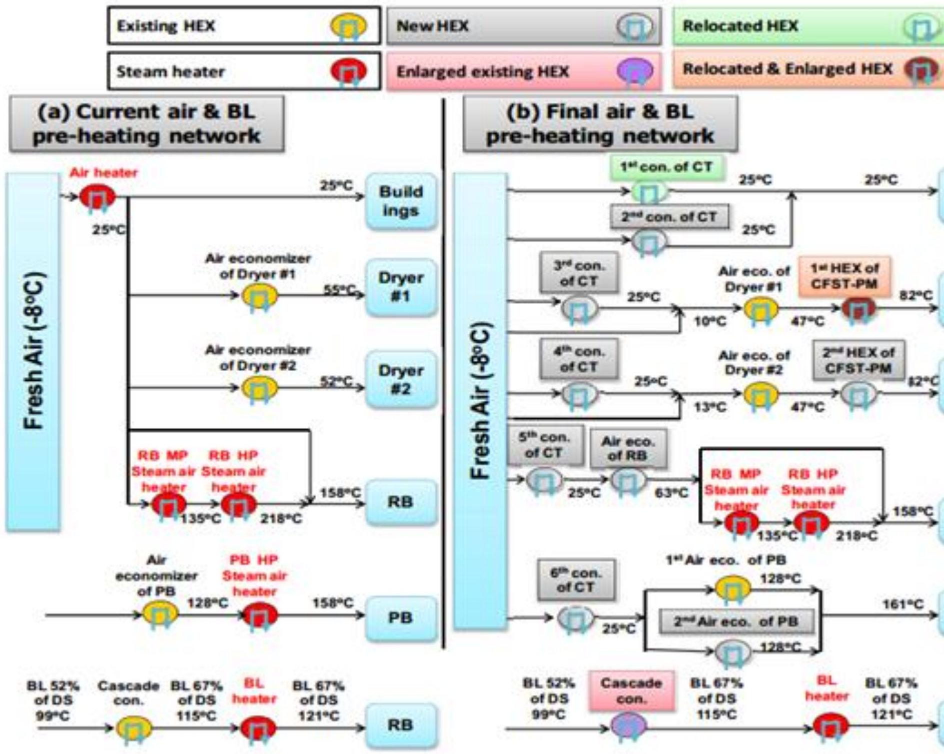


Figure 3.6: Mill A. Current (a) and final (b) air and black liquor (BL) pre-heating network.
RB: recovery boiler, PB: power boiler, PM: pulp machine, eco: economizer, MP: medium pressure, HP: high pressure, cascade con.: cascade concentrator, DS: dissolved solid, CFST: clean flashed steam of dryer, con. Condenser.

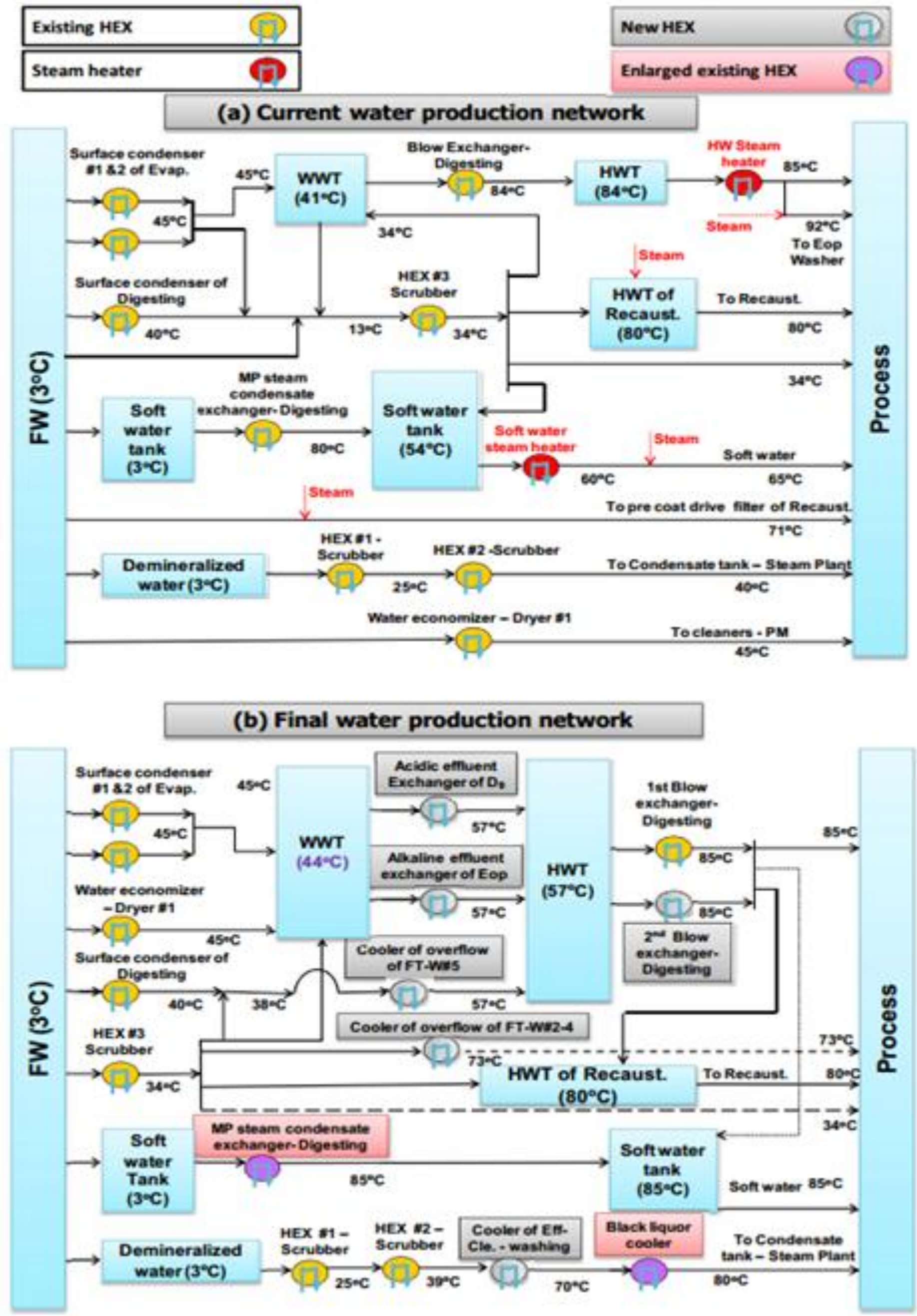


Figure 3.7: Mill A. Current (a) and final (b) water production network.
WWT: warm water tank, HWT: hot water tank, RB: recovery boiler, PB: power boiler, Eff-Cle.: effluent of cleaners

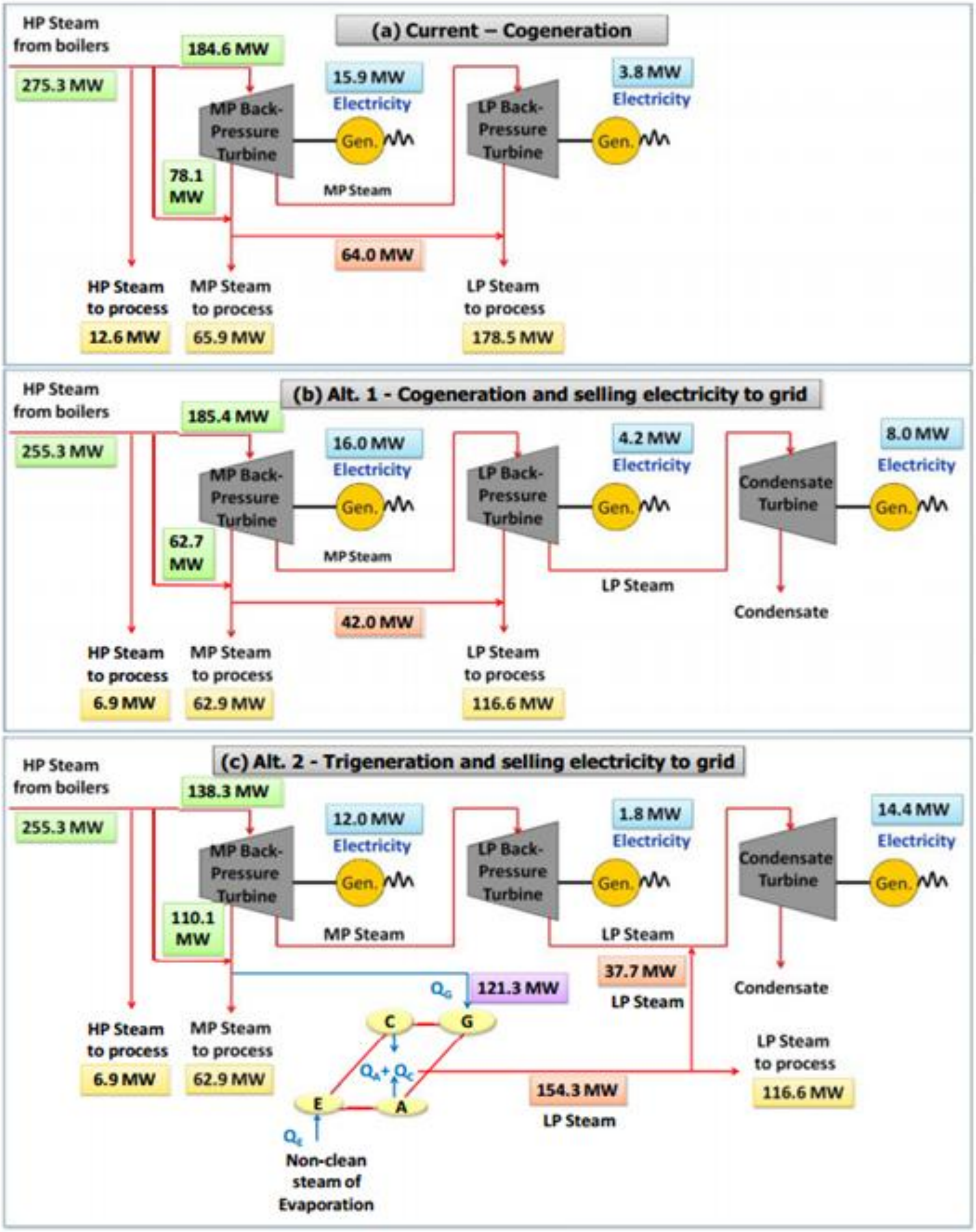


Figure 3.8: Mill A. Current cogeneration (a), Option 1 (b), and Option 2 (c).
G: generator, C: condenser, A: adsorber, E, evaporator, Gen: turbine generator.

IV. ANALYSIS OF MILL B

Mill B is a Kraft pulping mill, producing standard paper pulp. It incorporates two parallel but interconnected pulp lines. The average pulp producing rate is 1765 adt/d. The mill was built in the 1990's. The designation of the two pulp lines as Line 1 and Line 2 are the same as in the actual mill.

IV.1 Pre-benchmarking

Figures 4.1 and 4.2 illustrate the results of the pre-benchmarking step; they give an indication of the potential steam and water consumption savings. The mill departments forming the "others" category in Figure 4.1 are the steam plant, the inlet water treatment and conditioning and, the recausticizing plant. They also include the building heating requirements, which are not included in this study. The total steam consumption of this group initially at the 75th percentile of Canadian mills can be considerably reduced to 67% of its current value. The steam consumption of the black liquor evaporation system is higher than the 75th percentile because the concentrator of line 2, which raises the black liquor concentration of dissolved solids from 47% to 68 %, uses live steam. A more efficient process configuration will be proposed in section IV.4. The steam consumption of the pulp drying machine is slightly higher than the 75th percentile because, in both lines, low temperature water (40-65 oC) is used in the pulp machine and the exhaust air temperature in the dryer outlet is exceptionally high (132 oC vs. typically 75 to 90 oC). The steam consumption in the bleaching and chemical making departments, which is already below the 25th percentile, could be further reduced by about half by using higher temperature water as indicated in figure 4.1. The digesters are operating at a mid-point between the 50 and 75th percentile and it is unlikely that it could be improved. The combined effects of the possible steam consumption reduction would bring the total consumption of the mill from the 75th percentile to below the 25th percentile. There are significant opportunities for steam savings in mill B.

Figure 4.2 gives the water consumption for the main departments compared to reference data. It shows that water usage is well managed by the mill. The primary reason for this good performance is that, the consumption of water in the bleaching department is almost half that of mills designed in the 1980s. Small additional improvements could be made in several departments and further reduce the current consumption of water by 25%. This would bring the performance of the mill to a significantly better level.

The potential steam and water savings given by equations 1 and 2 are 38% and 24%, respectively.

IV.2 Energy (Water and steam) efficiency analysis

IV.2.1 Enhanced water systems analysis

The enhanced water pinch analysis was performed for line 1 and line 2. Key results are given in Table 4.117. The changes in fresh water utilization and filtrate reutilization made on the basis of water pinch analysis are illustrated in Figures 4.3 to 4.5 for line 1 and in Figures 4.6 to 4.8 for line 2. Diagram a in each figure gives the current configuration of the water system and diagram b shows the proposed configuration. Dashed purple lines indicate the change in the flow rate of the existing connections and the dotted red lines show the new connections. There are 28 changes in existing connection flow rates and 29 new connections for filtrate reutilization would be required for line 1; for line 2 the number of changes in existing connections is 17 and 8 new connections would be required. The total amount of water that could be saved is 350 m3/h that is 23% of current consumption for line 1 and 348 m3/h that is 25% for line 2, respectively. The total mill effluent would decrease by 706 m3/h that is 24% of its current level. It is worthy to note that although the total number of changes made to line 1 is more than double to the number of changes made to line 2 (57 vs. 25), the amount of water saved is approximately the same for both lines.

[17] Tables and figures of section III, IV and V are at the end of each section

IV.2.2 Steam systems analysis and enhancement

The steam consumption of the mill by user type after the analysis of the steam distribution system has been performed is displayed in Table 4.2 for line 1 and in Table 4.3 for line 2.

Line 1: There are four steam heaters in group a that cannot be modified; their aggregate consumption is 72.1 of MW, which accounts for 39.5% of the total current consumption. The steam consumption of steam heaters of group b can be completely eliminated either by the replacement of steam with another heat source (heaters 2, 3 and 4) or by upgrading a heat exchanger. The corresponding steam savings is 32.3 MW, i.e., 18% of current consumption. In the case of steam injection, there are no existing injection points in group c that could be practically replaced by heat exchangers. However, the quantity of steam injected in group d can be substantially reduced by using higher temperature water and shifting the heat load from steam to water. The impact of the two techniques is particularly important for the pulp machine where the steam consumption by the shower and predryer initially of 23.4 MW is completely eliminated. For the bleaching department the steam consumption is reduced from 23.1 MW to 10.5 MW, which is by more than half. The steam consumption by the deaerator is reduced by the adjustment of its operating conditions (the gain is 1.1MW) and more significantly by upgrading the heat exchanger network (the gain here is 4.3 MW). The cumulative impact of these measures is considerable since the steam consumption by group d is reduced from 66.2 MW to 29.2 MW, i.e., by 42.0 MW or 63%. As will often be the case, the injection points of the last group could not be rearranged nor replaced. The total steam savings that can be achieved by the implementation of the complete enhancement program in line 1 is 74.3 MW or 41% of current consumption.

Line 2: There are five steam heaters in group a that consume 124 MW of steam and that cannot be modified. In group b, it is expected that steam heaters 1 and 2 can be eliminated by upgrading heat exchangers. For the third steam heater, the steam can be completely replaced by another heat source. In the first group (group c) of steam injection points, the steam injection in the filtrate tanks of the pulp machine can be reduced from 6.5 to 3.7 MW. Once this change is implemented, the three injection points can be replaced by heat exchangers. The steam injection points of group d can be reduced from a requirement of 72.6 MW to 44.6 MW by applying the same saving measures as for line 1. Finally, the injection points of the last group could not be rearranged nor replaced.

Table 4.4 summarizes the aggregate results of the steam system analysis for both lines. The global difference between the two lines is primarily due to pulp processing capacity (line 1: 805 t/d; line 2: 960 t/d); on a per tonne basis, the steam consumption is 19.6 GJ/odt for line 1 and 22.5 GJ/odt for line 2. It should be noted that the reduction of steam consumption for line 1 was 41% and only 27% for line 2. Taking into account the current consumption of each line and potential savings, the total reduction of steam consumption for the two lines is 33% of the current value

IV.3 Identification of steam and water efficiency enhancement projects

The new process configurations based on the results of the water and steam systems analysis are displayed in Figures 4.3 to 4.5 for line 1 and in Figures 4.6 to 4.8 for line 2. Table 4.5 presents a global summary of the proposed projects for the two lines and the steam and water savings that they produce. The capital cost requirements are for new piping in the water network and for the installation of the new or upgraded heat exchangers. The increment of operating cost linked to the operation of the additional equipment has also been estimated. The total steam savings are 146.2 MW or 33% of current steam consumption. The total water savings are 695 m3/h that is 24% of current water consumption. The 60 projects entail 29 and 8 new connections for lines 1 and 2, respectively. The flow rates in existing process streams have been modified in 28 and 17 instances for line 1 and 2, respectively. The capital cost for changes in the mode of heat delivery is essentially related to piping and instrumentation. The capital and operating costs for equipment performance adjustments incorporate the installation of additional flash tanks. The capital and operating cost for the heat exchanger network upgrading is primarily related to the increase heat exchanger areas.

Two major performance improvement projects on the deaerators of each line must be highlighted. They concern the installation of a flash tank to recover 4.2 MW of steam from the blowdown water of the boilers (recovery boilers of line 1 and line 2 and power boiler of line 2). The reduction of the steam consumption by the deaerator would be 1.1 MW in line 1 and 3.5 MW in line 2. Also, the equivalent displacement ration (EDR) of washer #4 of line 1 is somewhat smaller than the target value (0.55 vs. 0.58). The performance of this washer could be upgraded by increasing the filtrate input from 354 to 365 t/h as indicated in Figure 4.3b.

IV.4 Retrofit design of the heat exchanger network

The existing heat exchanger network affected by the retrofit operation consists primarily of the air preheating and the warm and hot water production networks. The heat is supplied by process streams or steam heaters (Tables 4.2 and 4.3). Figures 4.9a to 4.11a show the heat exchanger networks of both lines before the retrofit design while Figures 4.9b to 4.11b give the new heat exchanger networks of both lines after retrofit design.

Figure 4.9b displays the preheating system for the boilers and dryers of both lines as well as the air preheating systems for buildings. New heat exchangers to be purchased include one condenser for the condensing turbine of each line and two air economizers for the pulp dryer and recovery boiler of line 2. Two heat exchangers currently used as air heaters for the two boilers and for space heating are relocated. Their new functions are as first condensers to the turbines of line 1 and line 2. The current air heater of the recovery boiler of line 1 would be upgraded and relocated as first air economizer of the dryer of line 2. Figures 4.10b and 4.11b illustrate the new heat exchanger network for the warm and hot water production of lines 1 and 2. There are 13 new heat exchangers required by the retrofit design of this network (five in line 1 and eight in line 2). The green liquor cooler of both lines could be enlarged to produce hot water at 84oC. The water heater #2 of line 1 could be relocated and used as a cooler for the clean flashed steam of the pulp machine of line 1. The water heater #1 on line 1 could also be relocated and enlarged in order to replace the existing and non-efficient cooler of non-clean steam digester on line 2. This process upgrade is possible because the current heat recovery is substantially lower than the amount of heat available. The contaminated water heater could be relocated and used as the first cooler of the blowdown water of the recovery and power boilers of line 2. The blow down cooler of the line 2 digester could be enlarged and used as the 2nd blow cooler. The water heater of line 2 could be relocated and enlarged in order to be used as the 2nd cooler of the blowdown water of the recovery and powerboilers of line 2. Finally, the condensate cooler of the pulp machine of line 2 could be enlarged and used to raise the temperature of the white water of the line 2 paper machine.

The implementation of the heat exchanger network has an impact on the steam requirement of the mill. This impact can be appreciated by comparing the last two columns of tables 4.2 and 4.3. The data given in column "HEN Upgrading" are based on the assumption that there are no constraints on the network retrofitting while the column "Final" integrates process constraints, which are not related to the steam distribution network.

In both lines, the impact is apparent in group d (reducible steam injection). For line 1 the increase in steam consumption is 6.8 MW and for line 2 it is 11.6 MW. In both cases the impact is small compared to the overall reduction, which is 74.3 MW in line 1 and 71.9 MW in line 2.

IV.5 Energy conversion and upgrading

In the current configuration of the mill there is a cogeneration unit installed on each line. It consists of two back pressure turbines producing medium pressure and low pressure steam and 48.9 MW of electricity as indicated in Figure 4.12a. The power plant of the mill consists of the recovery boiler and a power boiler using bark as fuel. Four options have been examined for the utilization of the steam production capacity liberated by the reduction of the steam consumption by the mill; they are illustrated in Figure 4.12, sections b, c, d, and e. The four options are ordered in increasing technical complexity:

Option 1 involves adding a back pressure turbine to the cogeneration plant to maximize electricity production;

Options 2 and 4 consist of adding an absorption heat pump to either option 1 or option 2

Option 3 consists of simply redirecting excess steam production capacity;

In Option 1, the excess steam discharged by the second turbine is partially used to drive a steam condensing turbine and thus generate electricity to be sold to the grid. The total capital cost for this option would be 12.6 M$ and the operating cost would be 1.17 M$/a for an exportable power capacity of 47.6 MW.

In Option 2, an absorption heat pump would be added to the previous cogeneration system.18 The heat pump would be driven by steam discharged from the first turbine. Non clean steam from the surface condenser of the warm water producing systems (Figures 4.10 and 4.11) would be used as the heat source in the pump evaporator. The pump would generate 335.9 MW of clean low pressure steam that would be used in part to drive the condensing turbine and in part as heat for the process requirements. The heat withdrawn from the warm water producing systems could be made up by adjustments in the retrofit design of the heat exchanger network. This option would produce a small increase in power generation (3.5 MW). The condenser and generator of the heat pump generate 335.9 MW if low pressure steam, which is used in part to drive the condensing turbine and in part sent to the process. The net steam production of the heat pump is 81.6 MW of low pressure steam. The net increase of electricity production vs. the base case is 27.4 MW, only a modest 3.5 MW vs. option 2. The capital cost required by this option is 131 M$, more than 80% of which is being attributed to the heat pump; the operating cost is 4.1 M$/a.

In Option 3, the cogeneration unit is not modified but, it takes advantage of the reduction in steam consumption by the process: the excess steam discharged by the second turbine is in part sold to potential district consumers (158.5 MW).

In Option 4, the installed back pressure turbines are maintained and a heat absorption heat pump is added to the cogeneration unit to maximize the amount of low pressure steam available for sale. The specifications and process connections of the heat pump are the same as in option 2. The amount of steam available for sale is increased to 254 MW but the power generation is significantly reduced (by 10.4 MW). The required investments and operating costs for this option are 109.4 M$ and 2.7 M/a, respectively.

A cost analysis of the four options has been performed and the results are summarized in Table 4.6. The main economic factors are:

In options 1 and 3 the main capital cost item is the additional heat-exchange area required;

In options 2 and 4 the required capital cost investment is three times that of the two other options because of the installation of an absorption heat pump, a capital intensive piece of equipment.

In options 3 and 4, the sale of excess steam is the main contributor to profits while in options 1 and 2, the main contributor is the sale of electricity;

The economic attractiveness of the options will depend on the sale prices of steam or electricity. If the market for steam is weak, options 3 and 4 will not be profitable, but option 1 will be very attractive. On the other hand, if there is a high demand for steam, option 3 will be very profitable because of its smaller capital cost ($425M) and short payback time (2.1a).

IV.6 Implementation strategy

A step-wise strategy is proposed for the implementation of option 1 and option 3, which have been identified as potentially profitable, depending on the relative selling prices of electricity and steam. The steps are the same for both options.

Implementation of all water reutilization projects to reduce steam consumption as shown in Figures 4.3 to 4.8.

Implementation of all equipment adjustment projects to reduce steam consumption as shown in Tables 4.2, 4.3 and 4.4 and Figure 4.3.

Upgrading heat exchangers of the water network as shown in Figures 4. 10 and 4.11.

[18] See section 2.4 and Figure 2.4 for specifications and the installation of the absorption heat pump.

Upgrading heat exchangers of the air heating system as shown in Figure 4. 9.

In the case of option 3, additional equipment will be required for the delivery of steam to the gate of the mill. In option 1 the last step is the installation of a steam turbine to the cogeneration plant.

In the case of option 3, the total investment required will be 42.5 M$. The increased operating costs will be 1.1 M$ and the payback time 2.1 years. For option 1, the total investment required will be 53.4 M$, the increase in operating costs will be 2.2 M$ and the payback time 3.1 years. A flexible strategy combining options 1 and 2 that would enable the mill to take advantage of fluctuations in electricity and steam demand could be advantageous. It would be worthwhile to determine the economics of such strategy as a function of potential scenarios.

IV.7 Post-benchmarking

Figures 4.1 and 4.2 illustrate post-benchmarking results after all the proposed energy efficiency enhancement projects have been implemented. Figure 4.1 shows that the steam consumption for pulp bleaching and drying and other utilizations would be significantly reduced and this would bring the total steam consumption of the mill lower than the 25 percentile of Canadian mills. Figure 4.2 also shows that the water consumption of the mill has been reduced in key departments (pulp washing, bleaching and drying) as well as in the recausticizing loop.

The potential steam and water savings computed at the inset of the projects were 38% and 24%, respectively. The value achieved by the implementation of all water and steam saving projects are 33% and 24%, respectively. The initial projected steam saving was somewhat optimist but the water savings target was met.

Table 4.1 gives a comparison between the anticipated and achieved heat and water savings based on the enhanced water pinch method used in section IV.2.1.

Table 4.1: Mill B, lines I and 2. Results of water pinch analysis and actual results

	Line 1		Line 2	
	Water Pinch	Actual	Water Pinch	Actual
Pinch Point (PPM)	300		320	
Max. System Closure (t/h)	14900	17810	15600	22338
Min. Fresh Water (t/h)	4100	1190	7800	1062
Min. Effluent (t/h)	4100	1148	7600	936

Table 4.2 Mill B, line 1. Steam consumption, current and after steam utilisation analysis (MW)

#	Equipment	Current	Heat delivery	Equipment adjustment	HEN Upgrading	Final[1]
	a. Steam heaters with non-replaceable heat source					
1	Digester, Upper heater	4.1	4.1	4.1	4.1	4.1
2	Digester, Lower heater	3.1	3.1	3.1	3.1	3.1
3	Paper machine, Dryer	38.9	38.9	38.9	38.9	38.9
4	Black liquor, Evaporators	26.0	26.0	26.0	26.0	26.0
	Total a	**72.1**		**72.172.1**	**72.1**	**72.1**
	b. Steam heaters with replaceable heat source					
1	Recovery boiler, Air heater	3.1	3.1	3.1	0	0
2	Recaust., Contam. hot water heater (85°C)	4.9	0	0	0	0
3	Hot water heater #1 (80°C)	7.3	0	0	0	0
4	Hot water heater #2 (80°C)	17.0	0	0	0	0
	Total b	**32.3**	**3.1**	**3.1**	**0**	**0**
	c. Replaceable steam injection					
	Total c	**0**	**0**	**0**	**0**	**0**
	d. Reducible steam injection					
1	O_2 Bleaching, reactor	4.8	5.9	5.9	3.0	4.0
2	Eop Bleaching, steam mixer	6.4	9.2	9.2	2.8	4.2
3	D1Bleaching, steam mixer	3.9	3.0	3.0	0.8	1.3
4	E2 Bleaching, steam mixer	4.4	2.8	2.8	0.3	1.0
5	D2 Bleaching, steam mixer	3.6	0.5	0.5	0	0
6	Pulp machine, Shower	18.2	4.6	4.6	0	0
7	Pulp machine, Predryer	5.2	5.2	5.2	0	0
8	Steam Plant, Deaerator	19.7	19.7	18.6	10.5	13.7
	Total d	**66.2**	**50.9**	**49.8**	**17.4**	**24.2**
	***e.* Other steam injection**					
1	Digester, Steam vessel	10.6	10.6	10.6	10.6	10.6
2	Black liquor, Evaporators	1.4	1.4	1.4	1.4	1.4
	Total e	**12.0**	**12.0**	**12.0**	**12.0**	**12.0**
	Grand Total (MW)	**182.6**	**138.1**	**137.0**	**101.5**	**108.3**
	% of current consumption	**100**	**76**	**75**	**56**	**59**

Note 1: Final heat requirement after complete retrofit design of the heat exchanger network.

Table 4.3 - Mill B, line 2. Steam consumption, current and after steam utilisation analysis (MW)

Equipment	Current	Heat Delivery	Equipment Adjustment	HEN Upgrading	Final
a. Steam heaters with non-replaceable heat source					
1 Digester, Upper heater	15.1	15.1	15.1	15.1	15.1
2 Digester, Lower heater	9.7	9.7	9.7	9.7	9.7
3 Paper Machine, Dryer	38.9	38.9	38.9	38.9	38.9
4 Black liquor, Evaporator	23.9	23.9	23.9	23.9	23.9
5 Black liquor, Concentrator	36.9	36.9	36.9	36.9	36.9
Total a	**124.5**	**124.5**	**124.5**	**124.5**	**124.5**
b. Steam heaters with replaceable heat source					
1 Space air heater	14.7	14.7	14.7	0	0
2 Recovery & Power boilers air heater	6.0	6.0	6.0	0	0
3 Hot water heater (65°C)	3.6	0	0	0	0
Total b	**24.3**	**20.7**	**20.7**	***0***	***0***
c. Replaceable steam injection					
1 Pulp machine filtrate tank	6.5	3.7	3.7	0	0
2 Hot water (75°C)	8.1	0	0	0	0
3 Hot water (60°C)	5.0	0	0	0	0
Total c	**19.6**	**3.7**	**3.7**	**0**	***0***
d. Reducible Steam Injection					
1 Eop Bleaching, steam mixer	8.3	9.7	9.7	2.7	5.1
2 D1 Bleaching, steam mixer	4.8	6.8	6.8	3.5	4.0
3 E2 Bleaching, steam mixer	3.9	4.5	4.5	2.5	2.7
4 D2 Bleaching, steam mixer	3.1	5.5	5.5	0	0.9
5 Pulp machine, Shower	12.9	13.1	13.1	1.6	3.9
6 Steam Plant, Deaerator	39.6	39.6	36.5	22.7	28.0
Total d	**72.6**	**79.2**	**76.1**	**33.0**	**44.6**
e. Other injection points					
1 Digester, Steaming vessel	21.9	21.9	21.9	21.9	21.9
2 Black liquor, Evaporator	1.4	1.4	1.4	1.4	1.4
3 Steam plant	0.4	0.4	0.4	0.4	0.4
Total e	**23.7**	**23.7**	**23.7**	**23.7**	**23.7**
Grand total (MW)	264.7	251.8	248.7	181.2	192.8
% of current consumption	100	87	86	63	67

Note 1: Final heat requirement after complete retrofit of the heat exchanger network

Table 4.4: Mill B, lines 1 and 2. Aggregate summary of steam utilization analysis (MW)

# Type of steam user (Refer to tables 4.2 & 4.3)		Current	Heat Delivery	Equipment adjustments	HEN Upgrading	Final
			Line 1			
1 Steam heaters	a	72.1	72.1	72.1	72.1 0	72.1 0
2 Steam heaters	b	32.3	3.1	3.1		
3 Steam Injection	c	0	0	0	0	0
4 Steam Injection	d	12.0	12.0	12.0	12.0	12.0
5 Steam Injection	e	66.2	50.9	49.8	17.4	24.2
Total		***182.6***	***138.1***	***137.0***	***101.5***	***108.3***
% of current consumption		-	***76%***	***75%***	***56%***	***59%***
			Line 2			
1 Steam heaters	a	124.5	124.5	124.5	124.5 0	124.5 0
2 Steam heaters	b	24.3	20.7	20.7		
3 Steam Injection	c	19.6	3.7	3.7	0	0
4 Steam Injection	d	23.7	23.7	23.7	23.7	23.7
5 Steam Injection	e	72.6	79.2	76.1	33.0	44.6
Total		***264.7***	***251.8***	***248.7***	***181.2***	***192.8***
% of current consumption		-	***95%***	***94%***	***68%***	***73%***
			Whole Mill			
1 Steam heaters	a	196.6	196.6	196.6	196.6 0	196.6 0
2 Steam heaters	b	56.6	23.8	23.8		
3 Steam Injection	c	19.6	3.7	3.7	0	0
4 Steam Injection	d	35.7	35.7	35.7	35.7	35.7
5 Steam Injection	e	138.8	130.1	125.9	50.4	68.8
Total, Whole mill		**447.3**	**389.9**	**385.7**	**282.7**	**301.1**
% of current consumption		-	87%	86%	63%	67%

Table 4.5- Mill B, lines 1 and 2. Summary of steam and water savings

Step	Nb of projects	Steam savings MW	Steam savings %	Water savings m³/h	Water savings %	Cap. cost M$	Oper. cost K$/a
Line 1							
Systems enhancement	17	44.5	24	350	23	4.36	-
Equip. Perfor. adjustments	1	1.1	1	-3	0	0.15	42
HEN upgrading	9	28.7	16	-	-	14.46	373
Total, line 1	**27**	**74.3**	**41**	**347**	**23**	**18.97**	**415**
Line 2							
Systems enhancement	13	12.9	5	348	25	0.98	-
Equip. Perfor. adjustments	1	3.1	1	-	-	0.35	118
HEN upgrading	19	55.9	22	-	-	19.68	494
Total, line 2	**33**	**71.9**	**27**	**348**	**25**	**21.01**	**612**
Whole mill							
Systems enhancement	30	57.4	13	698	24	5.34	-
Equip. Perfor. adjustments	2	4.2	1	-3	0	0.50	160
HEN upgrading	28	84.6	19	-	-	34.14	867
Total, Whole mill	**60**	**146.2**	**33**	**695**	**24**	**40.0**	**1027**

Table 4.6- Mill B. The economic benefit of savings from different resources [1]

	Effluent Reduction (m³/h)	Water saving (m³/h)	Savings (MW)	Elect. for sale (MW)	Steam sale (MW)	Effluent Reduct. (M$/a)	Water saving (M$/a)
Option 1: Cogeneration + sale of extra electricity	706 (25%)	695 (24%)	146.2 (33%)	24.1	-	0.6	0.1
Option 2: Trigeneration + sale of extra electricity	706 (25%)	695 (24%)	228.9 (51%)	27.7	-	0.6	0.1
Option 3: Sale of steam to local district	706 (25%)	695 (24%)	146.2 (33%)	-	158.5	0.6	0.1
Option 4: Trigeneration + sale of steam	706 (25%)	695 (24%)	228.9 (51%)	-10.4+	254	0.6	0.1
	Sale of electricity (M$/a)	**Sale of steam (M$/a)**	**Purchase of elect. (M$/a)**	**Increased oper. cost (M$/a)**	**Net profit (M$/a)**	**Total Cap. cost (M$)**	**Payback time (a)**
Option 1: Cogen + sale of electricity	18.5	-	-	2.2	17.0	53.4	3.1
Option 2: Trigeneration + sale of electricity	21.2	-	-	5.2	16.7	173.1	10.4
Option 3: Sale of steam to local district	-	20.4	-	1.1	20.0	42.5	2.1
Option 4: Trigen. + sale of steam	-	32.4	3.9	3.8	25.4	151.9	6.0

Note 1: the excess steam is sold to the local district, the capacity of electricity generation is reduced and electricity deficit should be purchased from grid

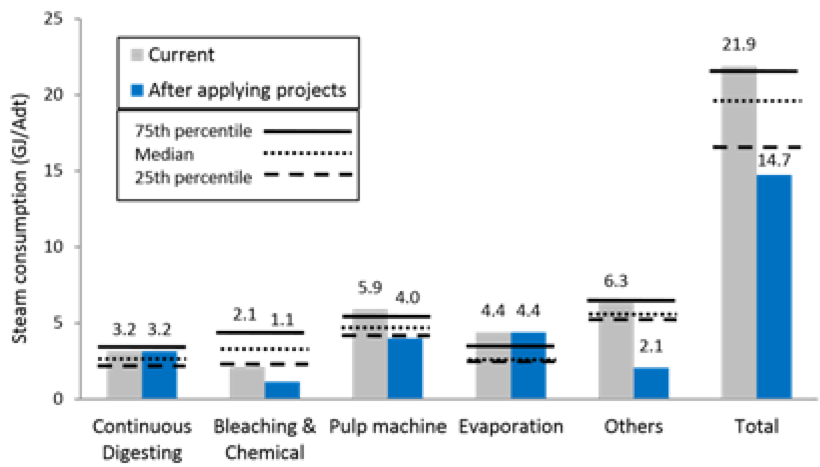


Figure 4.1: Mill B; Steam consumption of main departments and complete mill for current process configuration and after implementing performance enhancement projects

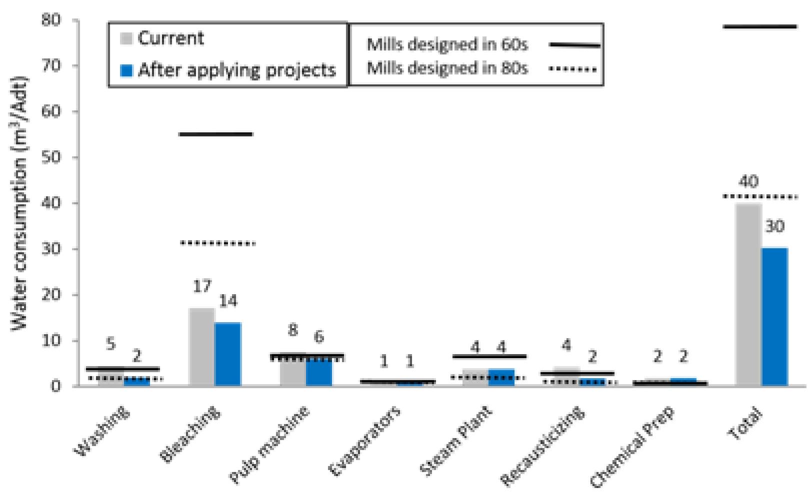


Figure 4.2: Mill B; Water consumption of main departments and complete mill for current process configuration and after implementing performance enhancement projects

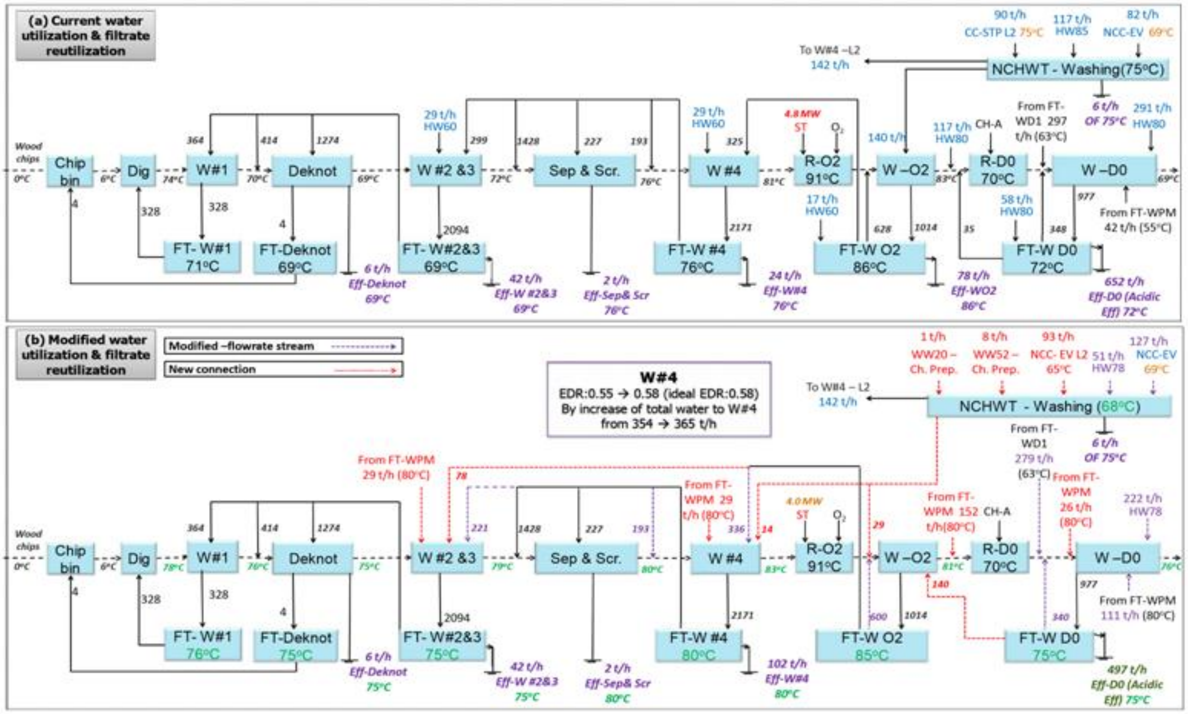


Figure 4.3: Mill B. Current (a) and final (b) water utilization and filtrate reutilization in the washing and bleaching departments. W: washer, FT: filtrate tank, Sep & Scr.: separators and screeners, Dig: digester, Deknot: deknotters, R: reactor, M: steam mixer, PM: pulp machine, NCHWT: non-clean hot water tank, CC-STP: clean condensate of steam plant, NCC-EV: non-clean condensate of evaporation, WW: warm water: FW: fresh water: HW: hot water, Eff.: effluent)

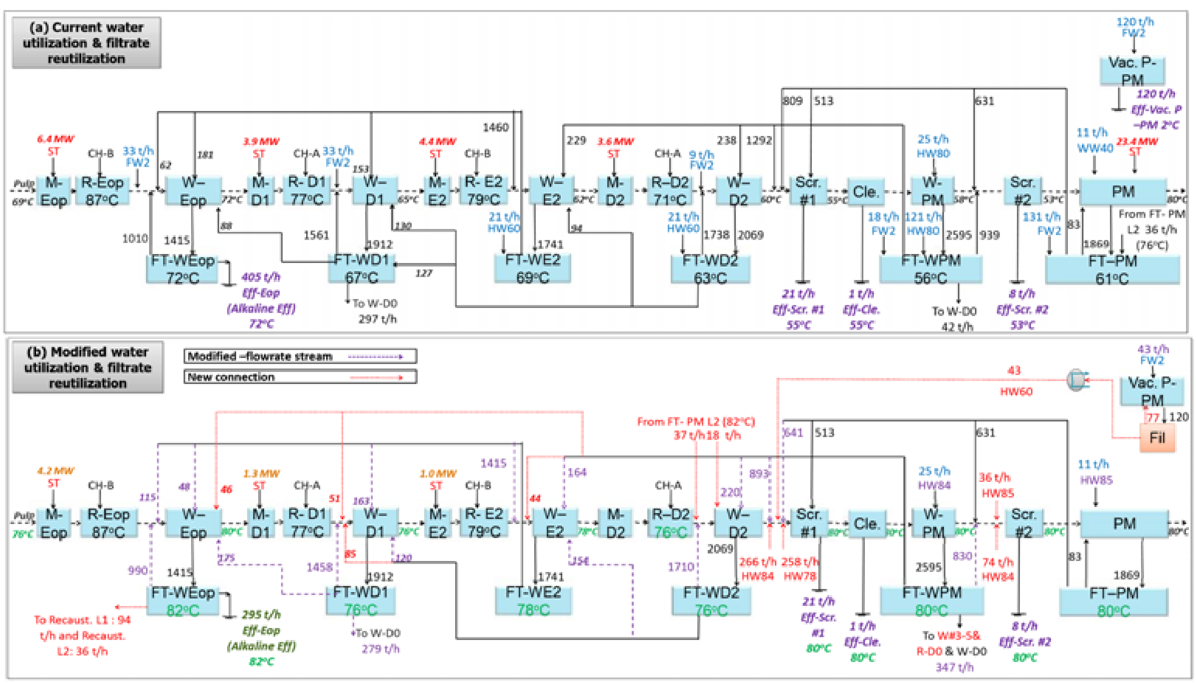


Figure 4.4: Mill B. Current (a), final (b) water utilization and filtrate reutilization in bleaching and pulp machine departments. W: washer, R: reactor; M: steam mixer, FT: filtrate tank, Cle.: cleaners, Scr.: screeners, PM: pulp machine, Vac. P: vacuum pump, Fil: filter, WW: warm water: FW: fresh water: HW: hot water, CH-A: acidic chemicals, CH- B: base chemicals, ST: steam, Eff.: effluent)

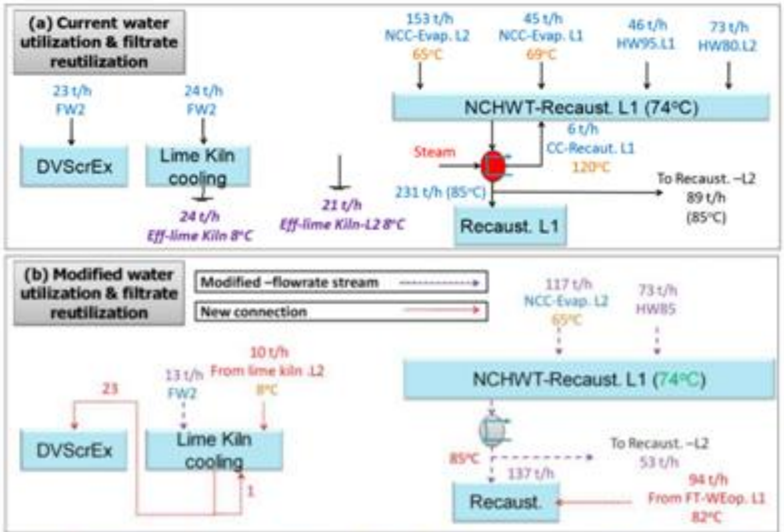


Figure 4.5 Mill B. Current (a) and final (b) water and filtrate utilization in recausticizing department.

DVScrEx: dust vent scrubber exchanger, NCHWT-Recaust.: non-clean hot water tank of recausticizing, FT-WEop: filtrate tank of washer Eop, NCC-Evap.: non-clean condensate of evaporation, CC: clean condensate, FW: fresh water: HW: hot water, Eff.: effluent)

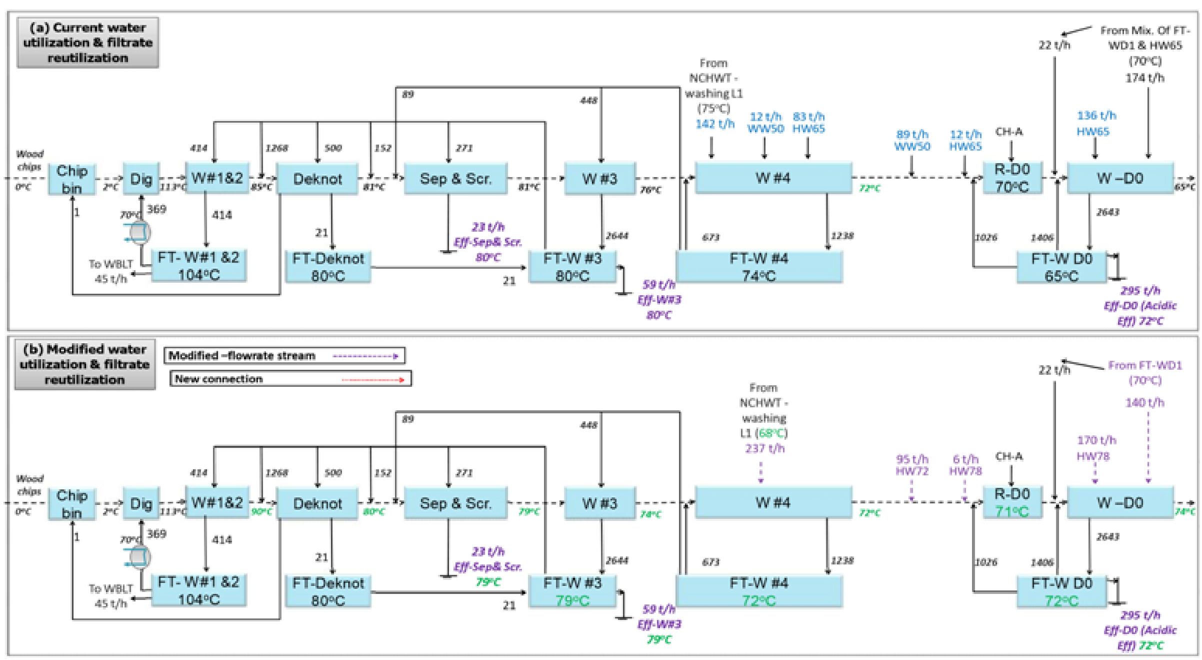


Figure 4.6: Mill B. Current (a) and final (b) final water utilization and filtrate reutilization in digesting, washing, and bleaching departments.

R: reactor, W: washer, FT: filtrate tank, Sep & Scr.: separators and screeners, Dig: digester, Deknot: deknotters, NCHWT: non-clean hot water tank WW: warm water: FW: fresh water: HW: hot water, Eff.: effluent)

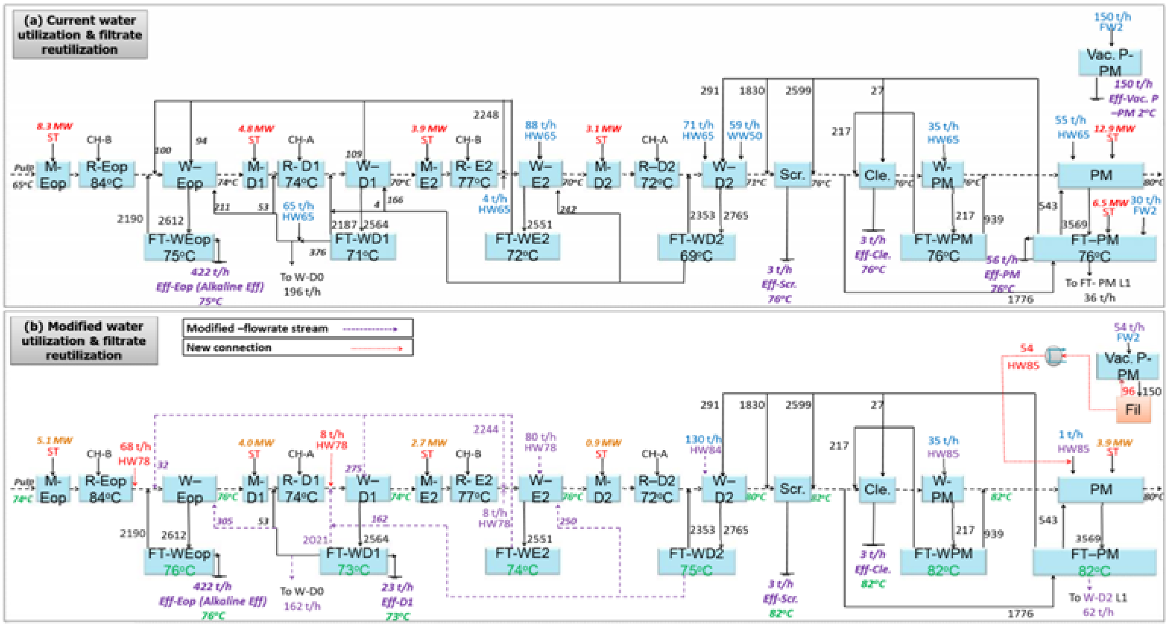


Figure 4.7: Mill B. Current (a) and final (b) water and filtrate utilization in bleaching and pulp machine departments.
W: washer, R: reactor; M: steam mixer, FT: filtrate tank, Cle.: cleaners, Scr.: screeners, PM: paper machine, Vac. P: vacuum pump, Fil: filter, WW: warm water: FW: fresh water: HW: hot water, CH-A: acidic chemicals, CH-B: base chemicals, ST: steam, Eff.: effluent)

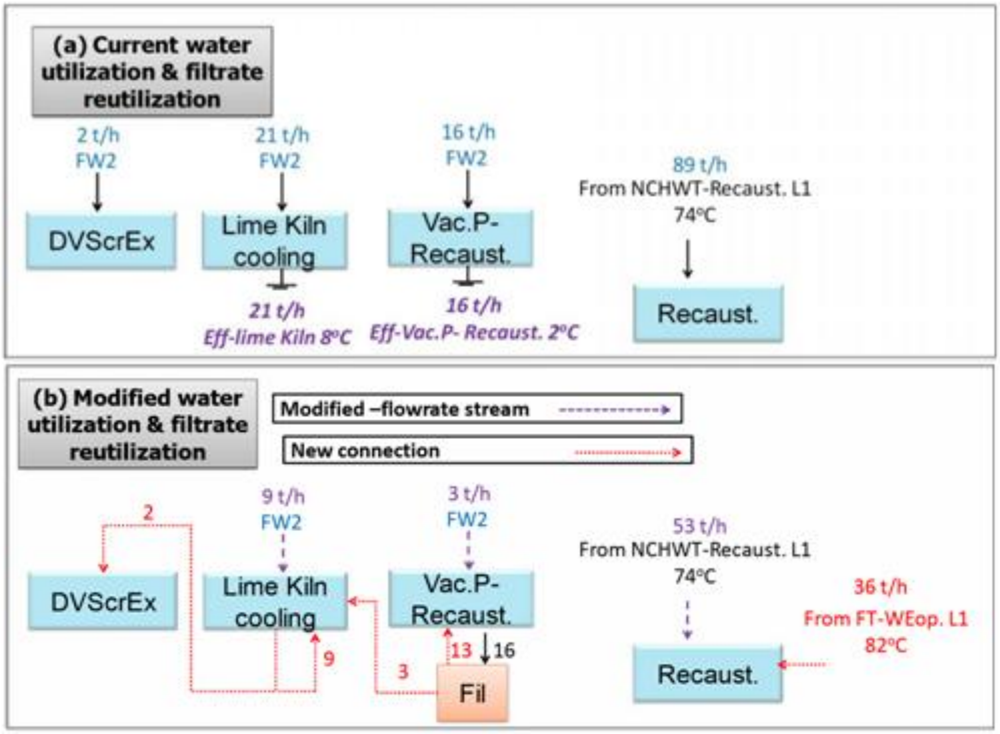


Figure 4.8: Mill B. Current (a) and final (b) water and filtrate utilization in recausticizing department.

DVScrEx: dust vent scrubber exchanger, Vac.P – Recaust.: vacuum pump of recausticizing, Fil.: filter, NCHWT-Recaust.: non-clean hot water tank of recausticizing, FT-WEop: filtrate tank of washer Eop, FW: fresh water: HW: hot water, Eff.: effluent)

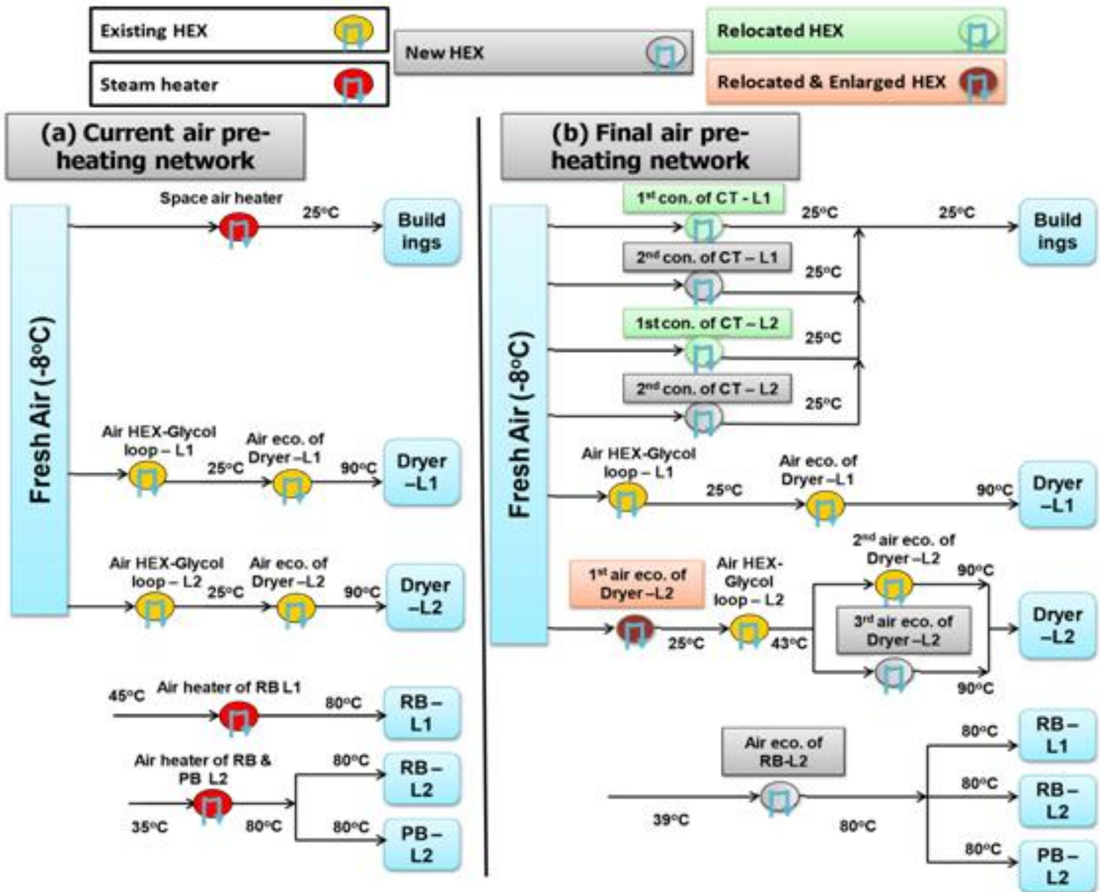


Figure 4.9: Mill B. Current (a) and final (b) air pre-heating network.

RB: recovery boiler, PB: power boiler, PM: paper machine, eco.: economizer, CT: condensing turbine, con.: condenser.

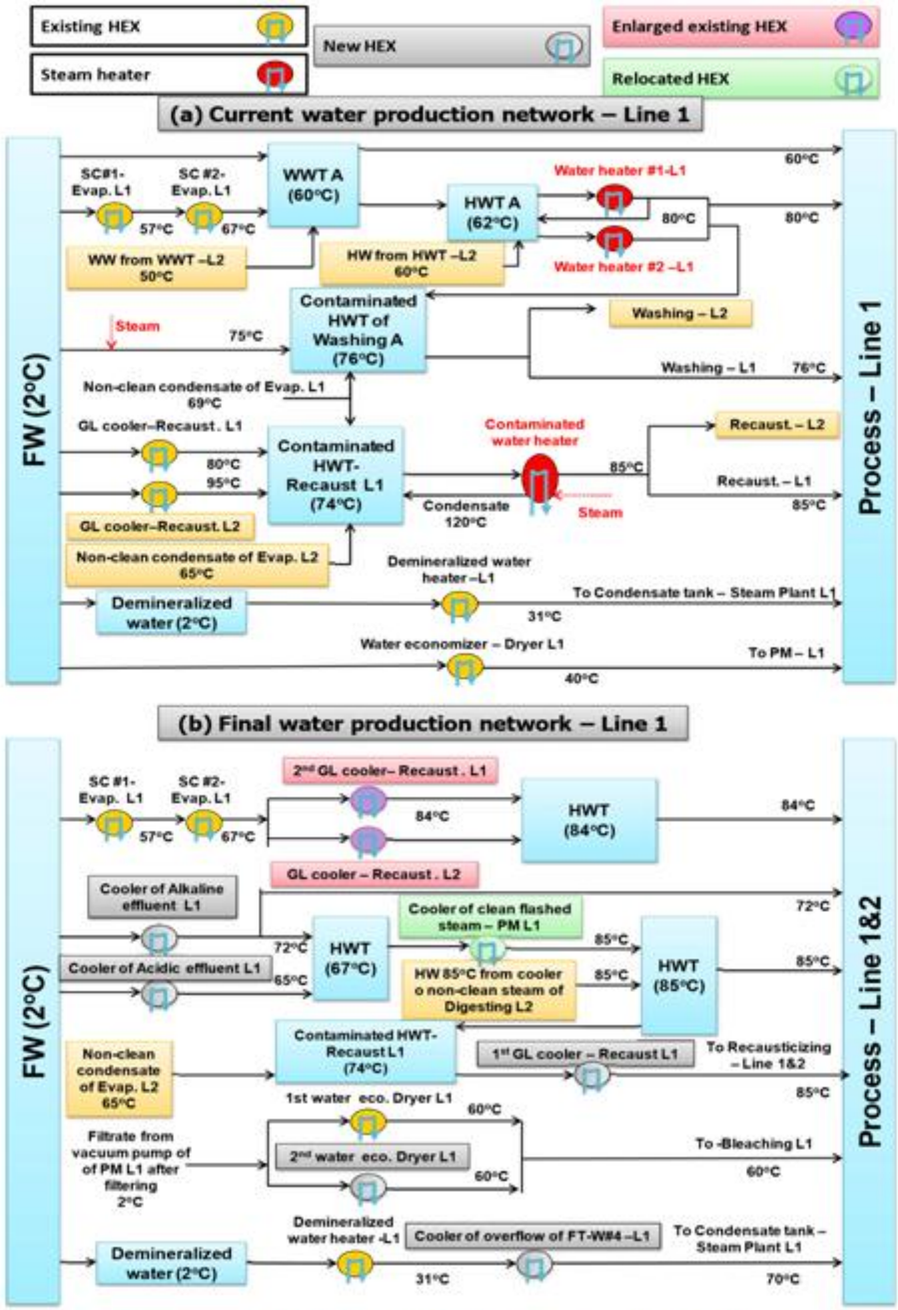


Figure 4.10: Mill B. Current (a) and final (b) water production network.

WWT: warm water tank, HWT: hot water tank, eco.: economizer, FT-W#4: filtrate tank of washer #4, PM: pulp machine, GL: green liquor, SC: surface condenser, Evap.: evaporation, Recaust.: recausticizing

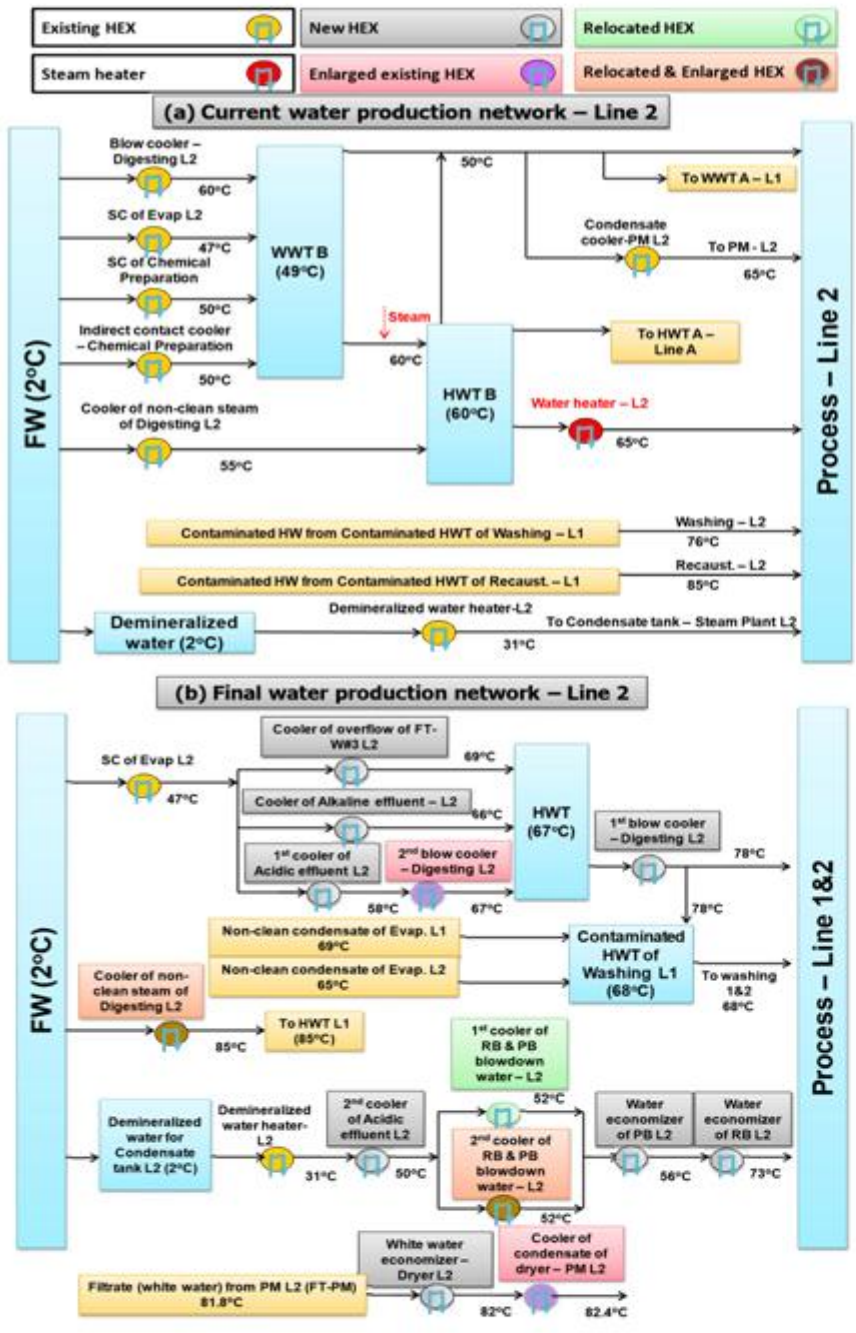
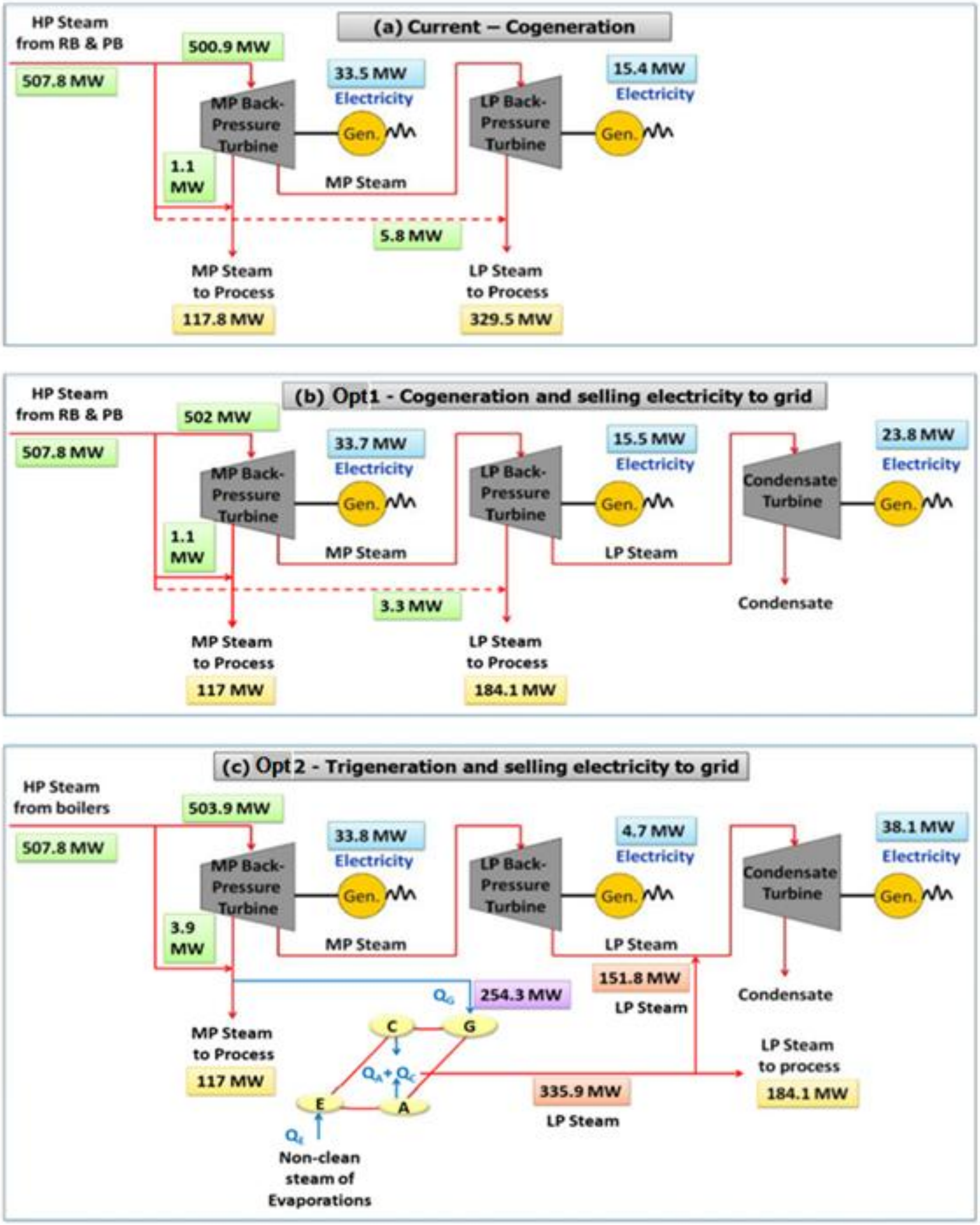


Figure 4.11: Mill B. Current (a) and final (b) water production network.
WWT: warm water tank, HWT: hot water tank, chem. SC: surface condenser, RB: recovery boiler.


(a) Current – Cogeneration
HP Steam from RB & PB
507.8 MW
500.9 MW
MP Back-Pressure Turbine
33.5 MW Electricity
Gen.
LP Back-Pressure Turbine
15.4 MW Electricity
Gen.
1.1 MW
MP Steam
5.8 MW
MP Steam to Process
117.8 MW
LP Steam to Process
329.5 MW
(b) Opt1 - Cogeneration and selling electricity to grid
HP Steam from RB & PB
507.8 MW
502 MW
MP Back-Pressure Turbine
33.7 MW Electricity
Gen.
LP Back-Pressure Turbine
15.5 MW Electricity
Gen.
Condensate Turbine
23.8 MW Electricity
Gen.
1.1 MW
MP Steam
LP Steam
3.3 MW
Condensate
MP Steam to Process
117 MW
LP Steam to Process
184.1 MW
(c) Opt 2 - Trigeneration and selling electricity to grid
HP Steam from boilers
507.8 MW
503.9 MW
MP Back-Pressure Turbine
33.8 MW Electricity
Gen.
LP Back-Pressure Turbine
4.7 MW Electricity
Gen.
Condensate Turbine
38.1 MW Electricity
Gen.
3.9 MW
MP Steam
LP Steam
151.8 MW
LP Steam
Condensate
Q_G
254.3 MW
C
G
Q_A+Q_C
E
A
MP Steam to Process
117 MW
335.9 MW
LP Steam
LP Steam to process
184.1 MW
Q_E
Non-clean steam of Evaporations

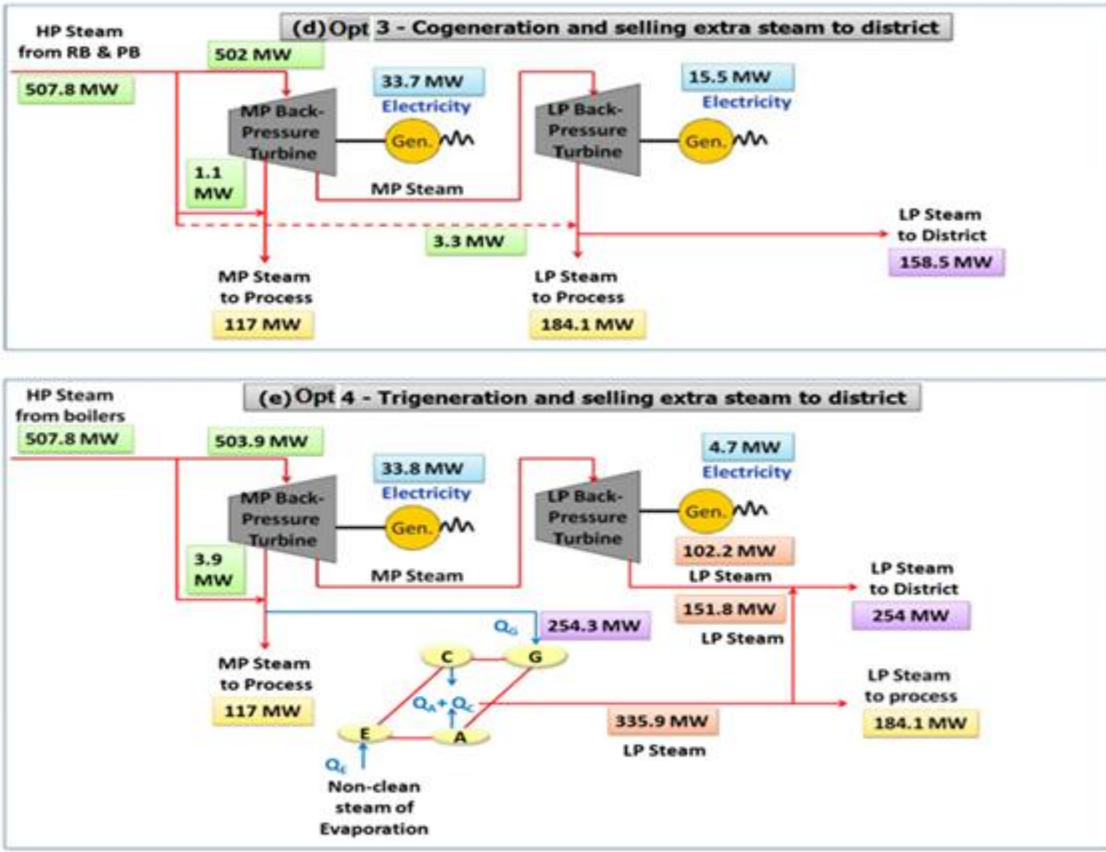


Figure 4.13: Mill B. Current cogeneration (a), Options. 1 (b), 2 (c), 3 (d) and 4 (e)

G: generator, C: condenser, A: absorber, E, evaporator, Gen.: turbine generator

V. ANALYSIS OF MILL C

Mill C manufactures a mixture of ground pulp (60%) and Kraft pulp (40%) from which publication paper grade is made. Only the Kraft pulping plant of mill C and a prorated fraction of steam and water consumption by the paper machine were taken into account in the energy efficiency analysis. The average pulp production rate of the Kraft mill is 280 adt/d. The core of the Kraft process was built in the 1930's but process upgrades were made later; the last addition (the paper machine) was done in the 1990's.

V.1 Pre-benchmarking

Figures 5.1 and 5.2 illustrate the results of the pre-benchmarking step. They give an indication of the potential steam and water savings. The mill departments forming the "others" category in Figure 5.1 are the steam plant, the inlet water treatment and conditioning and the recausticizing loop. The steam consumption of the digester is at the Canadian 75th percentile level (3.8 GJ/adt) and significant gains should be possible in this department. The possibility of reducing the steam consumption in the other departments, including the process share of the "others" group, will also be considered.

Figure 5.2 shows the water consumption for the main departments of the mill in comparison with reference data. Obviously, the water consumption in the pulp washing department is excessive probably because of inefficient counter current filtrate reuse. Instances of excessive water utilization could be attributed to the following practices:

High utilization of water in the washers (High DF and EDR) to minimize the bleaching agents consumption;

Insufficient reutilization of white water in other departments resulting in a large effluent from the filtrate tank of the paper machine.

It should be noted that there may be small discrepancies in some water streams because of the mixed feed to the paper machine.

V.2 Energy (water and steam) efficiency analysis

V.2.1 Enhanced water systems analysis

The enhanced water pinch analysis was performed. Key results are given in Table 5.1.[19] The changes in fresh water utilization and filtrate reutilization made on the basis of the water systems analysis are illustrated in Figures 5.3 to 5.5. Diagram a in each figure gives the current configuration of the water system and diagram b shows the proposed configuration. Dashed purple lines indicate the change in flow rate of the existing connections and the dotted red lines show the new connections. There are 11 changes in existing flow rates and 13 new connections for filtrate reutilization would be required. The amount of total water that could be saved is 994 m3/h that is 57% of the total water required for both mechanical and Kraft pulping lines. The total amount of sewered water sent to the effluent treatment system would decrease by 982 m3/h that is 58% of its current level.

V.2.2 Steam systems analysis and enhancement

The steam consumption of the mill by steam user type after the analysis of the steam distribution system has been performed is given in Table 5.2.

[19] Tables and figures of sections III, IV, and V are at the end of each section.

The six steam heaters of the first group currently consume 41.5 MW of steam, which is a sign of efficient design and operation. The consumption can be further reduced to 40.9 MW by adjustments to the two steam heaters of the digester. In the second group, the steam consumption by the glycol loop can be reduced from 7.6 MW to 2.3 MW by substituting a new heat source to heat the hot water. Further reduction to the steam consumption of steam heaters 1 to 5 can be achieved by retrofit design of the heat exchangers network. The single steam injection point of group c could be eliminated by using higher temperature water in the paper machine. The five steam injection points of group d currently consume 26.0 MW of steam. This can be reduced in two steps to 9.3 MW. A first aggregate reduction of 5.5 MW can be achieved by using higher temperature water in the process and the deaerator. All five steam injection benefit in various degrees from this operation. A second important reduction (10.2 MW) can be achieved by retrofit of the heat exchangers network. The beneficiaries of this operation are the Eop bleaching department and deaerator. Finally, in the last category of steam injection points, the consumption of the steaming vessel of the digester can be reduced from 6.1 MW to 3.5 MW with adjustments of the operating conditions.

V.3 Identification of steam and water efficiency enhancement

The energy efficiency enhancement projects derived from the results of the water and steam systems analysis are summarized below. There are six projects, one in the wood digester department, two in the pulp washing department and three in the power plant.

- ***Project 1:*** Digester.
  Process change: reduce heat losses to the environment by improved isolation of the cooking and the steaming vessels. The steam injected in the steaming vessel to heat up the wood chips and liquor to the desired temperature is 11.5 MW. This amount of thermal energy is much more than needed (based on a heat balance). Therefore there is a potential of steam reduction.

  Potential impact: reduced steam consumption (5.2 MW)

  This project requires additional investments for insulation of the steaming equipment.

- ***Project 2:*** Washers 3 and 4.
  Process change: reduced dilution factor (DF) from 6.7 to 4.6[20].

  Potential impacts: reduced water consumption (24 m^3/h), slightly increased feed of black liquor to recovery boiler (from 813 to 818 t/d) and, increased steam production (1.8 MW). Special care should be taken when implementing this project because the pulp quality should be maintained otherwise the consumption of ClO_2 and other bleaching agents may increase in the bleaching department. The final water utilization will be a compromise between water savings and bleaching agents cost.

- ***Project 3:*** Washer 5.
  Process change: reduced DF factor from 4.75 to 2.5, i.e. to the ideal value.

  Potential impact: reduced warm water consumption (27 m^3/h). Special care should be taken when implementing this project because the pulp quality should be maintained otherwise ClO_2 and other bleaching agents' consumption will increase in the bleaching department. The final water utilization will be a compromise between water savings and bleaching agents cost.

- ***Project 4:*** Recovery boiler.
  Process change: reduced heat loss by improved isolation and better cleaning of the boiler's heat exchangers tubes.

  Potential impacts: Increased steam production (16.9 MW), increased fresh water consumption (20 m^3/h) and increased steam consumption (3.7 MW) by deaerator.

- ***Project 5:*** Power boiler 1.
  Process change: reduced heat loss by improved isolation and better cleaning of the boiler's heat exchangers tubes.

[20] Ideal value of the dilution factor: 2.5

Potential impacts: increased steam production (1.1 MW), increased fresh water consumption (10.2 m^3/h) by deaerator.

Projects 4 and 5 are theoretically feasible. The heat transfer through the tubes of the power boiler and recovery boiler could be increased if the heat-transfer resistance is decreased. The resistance is decreased through thorough tubes cleaning. However, if the equipment is old, the washing and cleaning might not be a sufficient solution to this problem. This could be the case of this mill. Hence, additional investment could be required to replace a certain part of the equipment.

- ***Project 6:*** Deaerator.
  Process change: install flash blowdown and recycle steam produced to deaerator.

  Potential impact: reduction of steam consumption (2.9 MW)

The net aggregate gains by all projects to be implemented are as follows:
- Potential increased steam production capacity by boilers: 23.4 MW
- Reduced steam consumption by the digester: 4.2 MW
- Net increase of steam consumption by deaerator: 0.8 MW
- Reduced water consumption by washers: 51 m^3/h
- Increased water consumption by deaerator: 26 m^3/h

It should be noted that several projects identified in the course of the water systems analysis step are also incorporated in Figures 5.3 to 5.5. They are improvements to washers 3, 4, and 5 (projects 2 and 3) and to the deaerator (project 6).

Also, it is important to mention that these projects are the aggregate of a number of modifications displayed in details in tables 5.3 and 5.4.

The implementation strategy proposed in section V.6 does not take into account the investment plan of the mill nor the budget allocated to equipment enhancement or replacement.

V.4 Retrofit design of heat exchanger network

The parts of the existing heat exchanger network affected by the retrofit operation consist of the following, (i) the preheating of the air used by the recovery boiler, the power boilers, the dryer of the paper machine, and (ii) the production of the warm and hot utility water. The new heat exchanger network is displayed in Figures 5.6 and 5.7. The new network maximizes the use of process streams to supply heat and utilizes the air and water heaters already installed.

The current network used for air preheating and the proposed new network are shown in Figures 5.6a and 5.6b, respectively. The required new equipment is a condenser for the new condensing turbine and an air economizer to pre-heat the air used by the paper dryer and the recovery boiler. It must be noted that all boilers fired with natural gas (PB1, 3 and 6) can be shut down following the steam savings program mentioned in Section V.2.2.

The current heat exchanger network for hot and warm water heating and the proposed new network are shown in Figures 5.7a and 5.7b, respectively. Four new exchangers are required and two existing heat exchangers must be upgraded. The design of the new network is based on the adjusted temperatures of the hot and warm water used in the upgraded utilization side of the process given in Figures 5.3 to 5.5; they are T_{hot} = 81 and 70 ℃ and T_{warm} = 57 ℃. Also, four blowdown heat exchangers should be relocated to preheat the demineralized water added to the condensate tank of the power plant; this heat exchanger would use heat recovered from the blowdown water of the recovery boiler and power boiler 2.

V.5 Energy conversion and upgrading

Table 5.3 summarizes the overall steam and water savings that can be implemented in Mill C. The steam consumption would be reduced by 45% and the combined steam production capacity of the recovery boiler and the boiler maintained in operation (PB1) would increase by an amount corresponding to 21% of current consumption. The combined effects of those two factors are that an excess steam production capacity of 77.8 MW or 66% of current consumption could be created. This should first be used to shut down the three power boilers that are fired with natural gas (PB2, PB3 and PB6) and that produce together 64.5 MW of steam. The total elimination of natural gas as a fuel would represent a very substantial reduction in operating costs.

The recovery boiler and the power boiler 1, which is fired with bark, if maintained at their current operating rate would still produce 13.3 MW of steam over the new mill requirement provided the performance increase of the two boilers derived from improved maintenance (4.8 MW) is actually implemented. Therefore, it is assumed that the excess steam production capacity of the mill, once all the steam and water saving projects have been implemented, would be between 4.2 and 9.0 MW. This does not justify the installation of a cogeneration plant to sell electricity to the grid or other users. However, depending on economic conditions, i.e., cost of natural gas vs. sale price of electricity, keeping one or several natural gas fired boilers in operation to drive a cogeneration unit could be envisioned. The option to convert these boilers to wood biomass combustion could also be considered in connection with the installation of a cogeneration unit. However, this option was not part of the mandate of the present work and has not been treated.

V.6 Implementation strategy

The schedule of implementation of the steam and water savings projects should be coordinated with the shut down program of the power boilers 2, 3 and 6 which are fired by natural gas. It is recommended that the boilers be shut down in order of increasing steam production efficiency to accelerate the benefits derived from the implementation of steam and water savings projects. The recommended shutdown sequence is therefore: power boiler 6, the least efficient first and, power boiler 3, the most efficient last. The resulting three-phase strategy is summarized below.

Phase 1: Implementation of projects steam heaters upgrades (18.1 MW), upgrades performance of RB and B1 (23.4 MW) and shutdown of power boiler 6, (18.7 MW).

Phase 2: Implementation of steam injection system modification (31.9 MW) and shutdown of power boiler 2 (7.3 MW).

Phase 3: Implementation of digester and deaerator modifications (4.4 MW) and shutdown of power boiler 3, (38.5 MW).

Corresponding economic data are given in Table 5.4. The computation method and supporting data are given in sections II.3 and II.4. It could be advantageous to keep one of the power boilers in operation as a backup equipment to facilitate the plant operational management. The choice of the boiler to be kept in operation should be based on two factors: steam production capacity required and combustion efficiency.

V.7 Post-benchmarking

Figures 5.1 and 5.2 illustrate the post-benchmarking results after the three implementation phases have been completed. The steam consumption would be significantly reduced in all process departments and in the “others” group except in the black liquor concentration unit. As a result, the total steam consumption of the mill could be brought below the consumption of the 25th percentile of Canadian mills. The water consumption has been significantly reduced in the Kraft pulping line, primarily in the washing and bleaching departments. Small improvements have also been made in the digester department, the paper machine and the recausticizing loop. The total gains are 49.4 m3/adt, which places the consumption of the mill just above that of mills built in the 1980s.

The potential steam and water savings computed by equations 1 and 2 on the basis of the pre-benchmarking steps were respectively 41% and 53%. The actual values based on the results of the efficiency analysis of the mill are 45% and 58%, which is slightly above the anticipated results. The results of this study illustrate the effectiveness of the novel methodology.

Table 5.1- Mill C. Results of water pinch analysis and actual results

	Water Pinch	Actual
Pinch Point (ppm)	231	
Max. System closure (t/h)	9200	11150
Min. Fresh water (t/h)	2000	800
Min. Effluent (t/h)	1800	750

Table 5.2- Mill C. Steam consumption, current and after steam utilization analysis (MW)

	Department and Equipment	Current (MW)	Heat Delivery (MW)	Equipment Adjust.(MW)	HEN Upgrading (MW)	Final (MW)
	a. Steam heaters with non-replaceable heat source					
1	Digester, upper heater	3.8	3.8	3.4	3.4	3.4
2	Digester, lower heater	2.2	2.2	2.0	2.0	2.0
3	$NaClO_3$ heater #1 & 2 – Chemical preparation	0.1	0.1	0.1	0.1	0.1
4	Chemical reboiler – Chemical preparation	1.6	1.6	16.	1.6	1.6
5	Paper machine, Dryer	24.0	24.0	24.0	24.0	24.0
6	Black liquor Evaporators	9.8	9.8	9.8	9.8	9.8
	Total a	**41.5**	**41.5**	**40.9**	**40.9**	**40.9**
	b. Steam heaters with replaceable heat source					
1	Paper machine, Glycool loop	7.6	2.3	2.3	0	0
2	Paper machine, Air heater	4.6	4.6	4.6	0	3.0
3	Green liquor heater + Recaustification	1.1	1.1	1.1	0	0
4	Air heater – RB	6.8	6.8	6.8	0	1.8
5	Air heater – PB#3	1.9	1.9	1.9	0	0
6	Water heater – Chemical Preparation	0.3	0	0	0	0
	Total b	**22.3**	**15.6**	**15.6**	**0**	**4.8**
	c. Replaceable steam injection					
1	Paper machine, Silo Cheat	10.6	0	0	0	0
	Total c	**10.6**	**0**	**0**	**0**	**0**
	d. Reducible steam injection					
1	Bleaching, Pre-DO washer	0.2	0	0	0	0
2	Bleaching, DO washer	1.7	0	0	0	0
3	Bleaching - Eop	5.0	4.3	4.3	2.4	3.3
	WW production at steam ejector	1.8	0.3	0.3	0.3	0.3
4	Condenser , Chemical preparation					
5	Deaerator , Steam plant	17.3	14.9	15.8	6.3	5.7
	Total d	**26.0**	**19.5**	**20.4**	**90.**	**9.3**
	e. Other steam injection points					
1	Digester, Chip bin	5.4	5.4	3.5	3.5	3.5
2	Digester, Steaming vessel	6.1	6.1	3.4	3.4	3.4
	Total e	**11.5**	**11.5**	**6.9**	**6.9**	**6.9**
	Grand total (MW)	111.9	88.1	83.8	56.8	61.9
	% of current consumption		79%	75%	51%	20%

Table 5.3- Mill C. Summary of steam and water savings

Step	Nb. of mod.	Steam system		Other steam savings		Water savings		Cap. costs	Oper. costs
		MW	%	MW	%	MW	%	M$	K$/a
Heat delivery	14	23.8	21	-	-	994	57	1.72	-
Equipment adjustments	5	4.3	4	26.8	21	25	1	1.26	174
HEN upgrading	12	21.9	20	-	-	-	-	6.56	164
Total	31	50	45	26.8	21	101	58	9.54	338

Table 5.4: Mill C. Strategy of implementation of the steam and water savings modifications

	Phase 1	Phase 2	Phase 3	Total
Natural gas fired power boiler shut down	PB6	PB2	PB3	-
Number of modifications implemented	14	5	12	31
Steam consumption reduction (MW)	23.8	31.1	-	54.9
Water consumption reduction (m^3/h)	994	25	-	1019
Steam production increase (MW)	-	-	21.9	21.9
Capital investment required by projects (M$)	1.72	1.26	6.56	9.54
Operating cost increase (k$/a)	-	174	164	338
Natural gas cost reduction (M$/a)	4.4	1.4	7.2	13
Total operating cost reduction (M$/a)	4.4	1.4	7.2	13
Cogeneration Unit Investment Cost (M$)	-	-	7.7	7.7
Electricity Generation Revenue (M$)	-	-	6.4	6.4
Payback time (a)	0.4	0.9	0.9	0.9

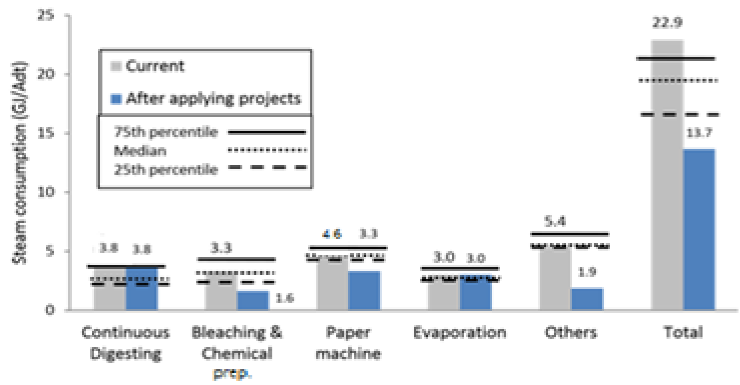


Figure 5.1: Mill C. Steam consumption for current process configuration and after implementing performance enhancement projects

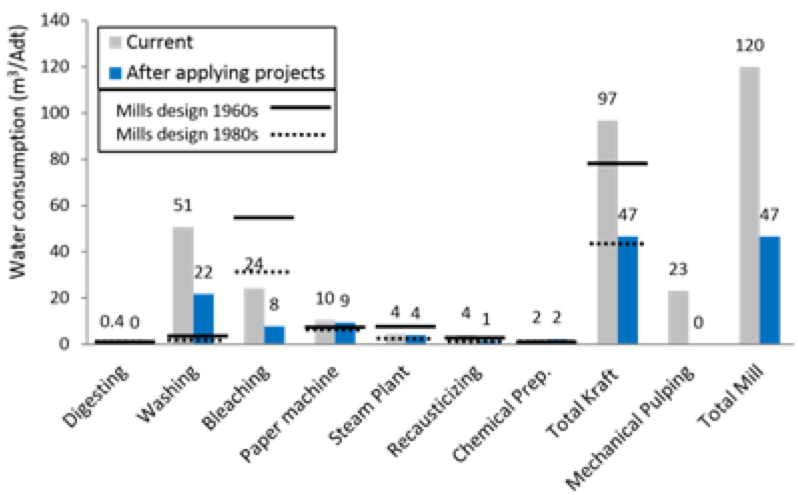


Figure 5.2: Mill C. Water consumption for current process configuration and after implementing performance enhancement projects

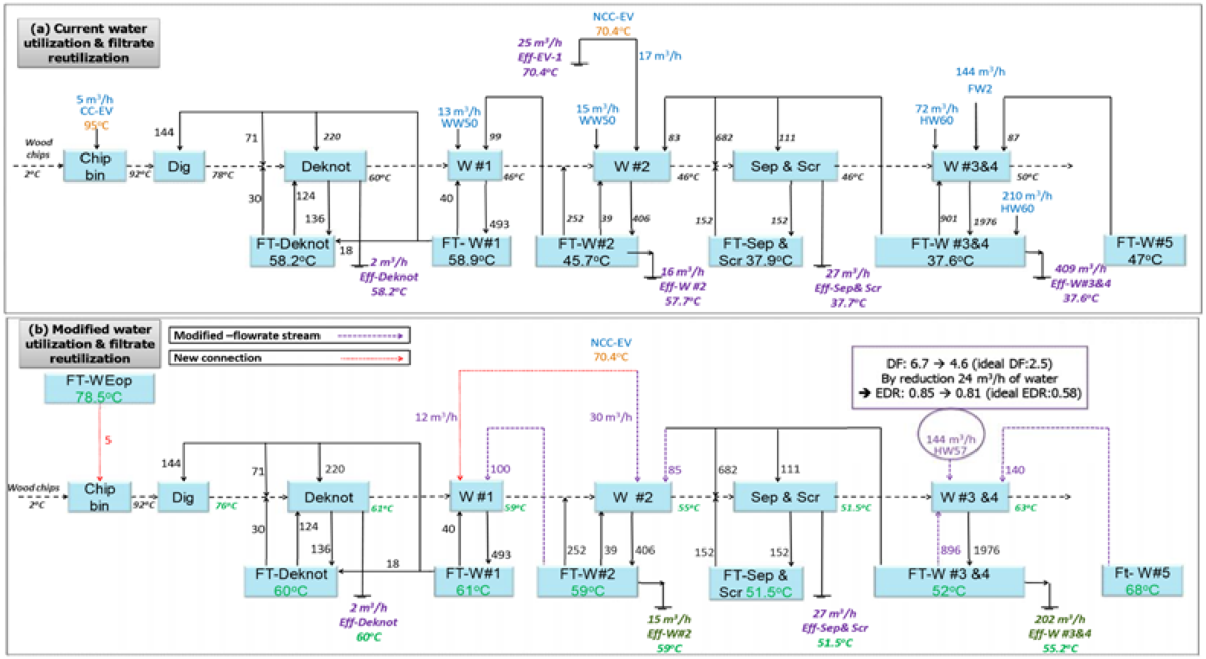


Figure 5.3 – Mill C. Current (a) and final (b) water and filtrate utilization in digesting and washing departments.
W: washer, FT: filtrate tank, Sep & Scr.: separators and screeners, Dig: digester, Deknot: deknotters, NCC-EV: non-clean condensate of evaporation, WW: warm water: FW: fresh water: HW: hot water, Eff.: effluent

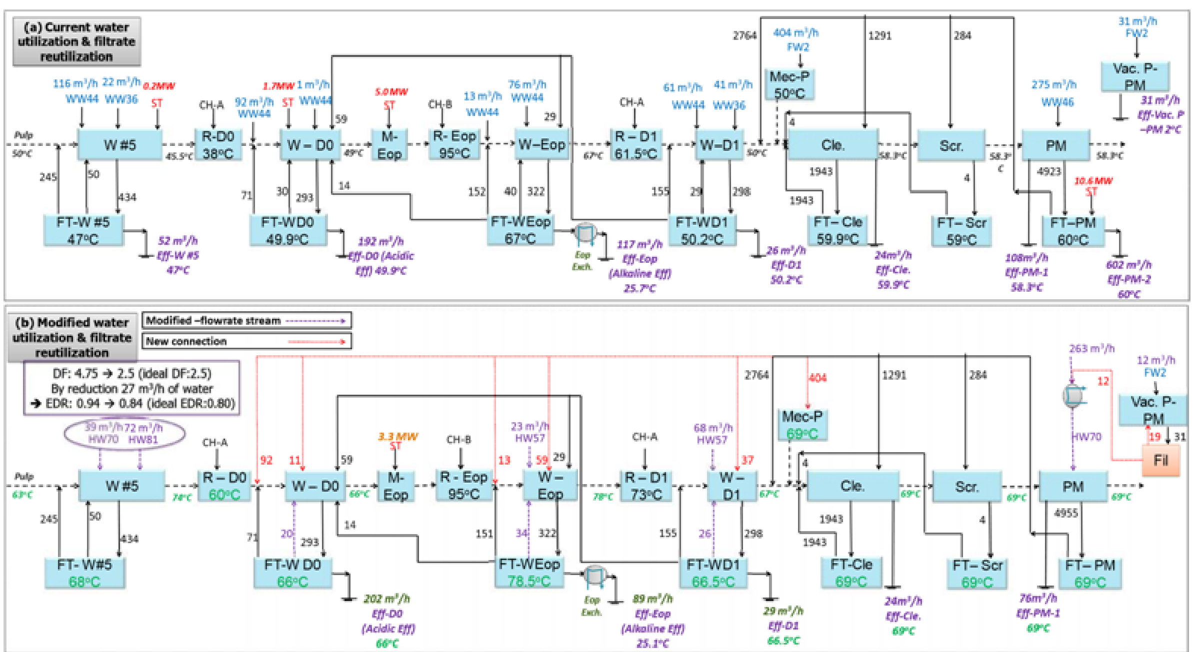


Figure 5.4 – Mill C. Current (a) and final (b) water and filtrate utilization in bleaching and paper machine departments.
W: washer, R: reactor; M: steam mixer, FT: filtrate tank, Mec.-P: mechanical pulping, Cle.: cleaners, Scr.: screeners, PM: paper machine, Vac. P: vacuum pump, Fil: filter, WW: warm water: FW: fresh water: HW: hot water, CH-A: acidic chemicals, CH-B: base chemicals, ST: steam, Eff.: effluent)

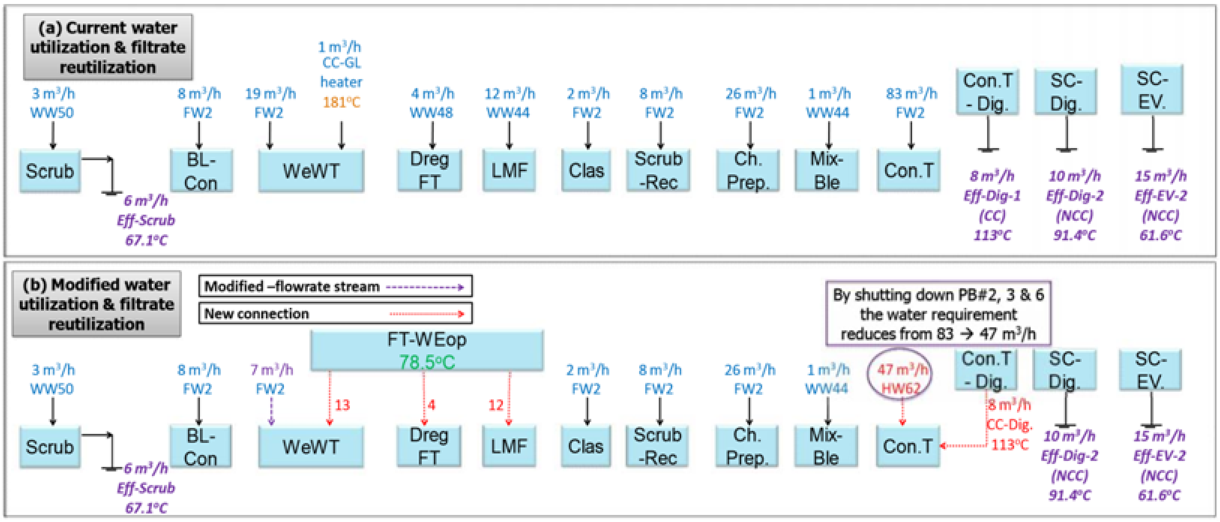


Figure 5.5 Mill C. Current (a) and final (b) water and filtrate utilization in scrubber, recausticizing, chemical preparation, and steam plant departments.

Scrub: scrubber, BL-Con: black liquor concentrator WeWT: weak wash tank, Dreg FT: dreg filter, LMF: lime mud filter, Clas: classifier, Scrub-Rec: scrubber of recauticizing, Ch. Prep.: chemical preparation, Mix-Ble: mixer-bleaching, Con. T: condensate tank, Con. T-Dig.: condensate tank of digesting, SC-Dig.: surface condenser of digesting, SC-EV.: surface condenser of evaporation, WW: warm water: FW: fresh water: HW: hot water, CH-A: acidic chemicals, CH-B: base chemicals, ST: steam, Eff.: effluent)

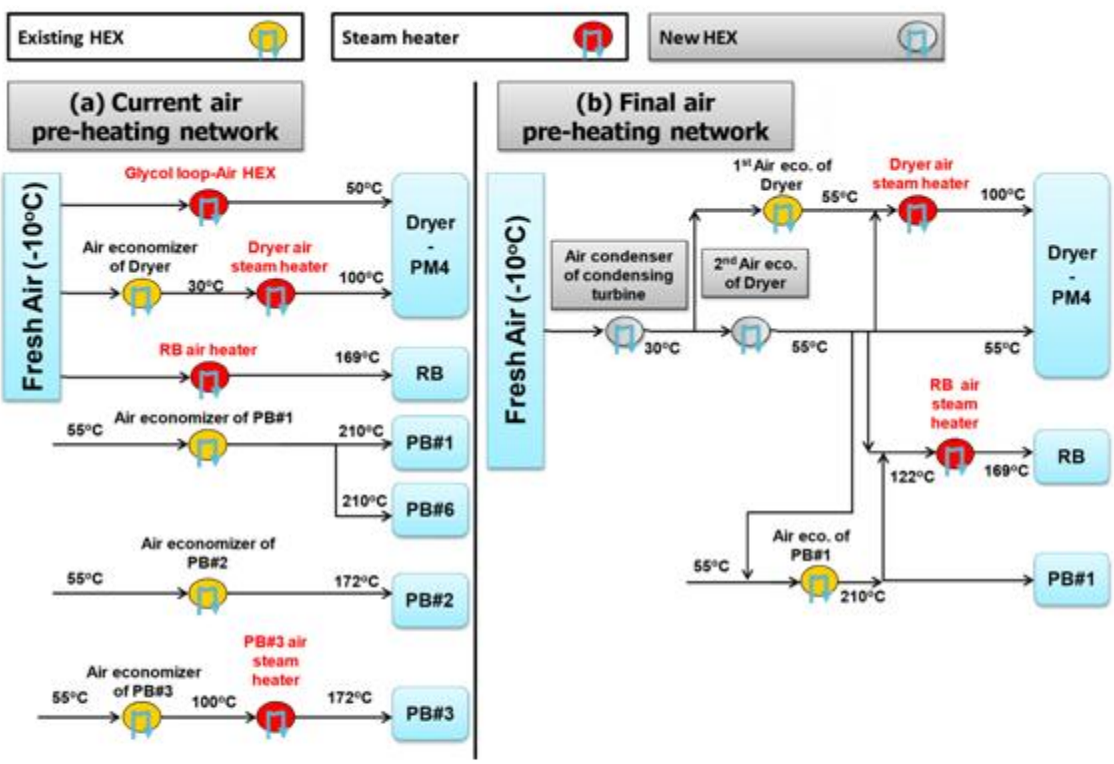


Figure 5.6 – Mill C. Current (a) and final (b) air pre-heating network.

RB: recovery boiler, PB: power boiler, PM: paper machine, eco.: economizer)

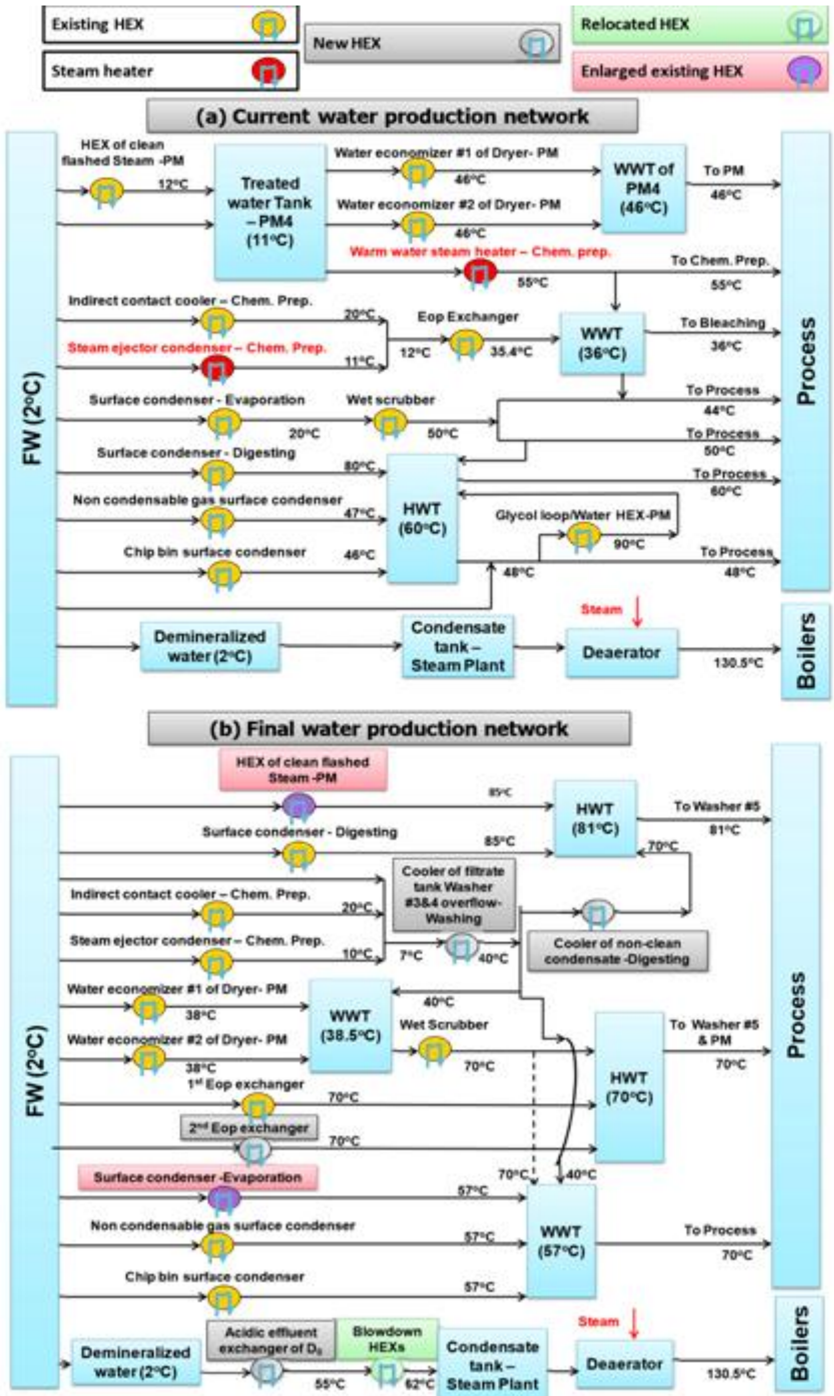


Figure 5.7 – Mill C. Current (a) and final (b) water production network.

VI. SYNTHESIS AND CONCLUSION

Key results of the analysis of the three mills are presented in Figure 6.1. The implementation of the proposed energy enhancement projects would liberate an excess steam production capacity of more than 25% of installed capacity and a reduction of water consumption of more than 20% in the three case studies. The results of this methodology are superior to those of previous studies applied to P&P mills mentioned in section II.6 that achieve energy savings ranging between 10 and 25% [49,57].

The results also show large differences in steam and water savings between the three mills. There are inherent factors, which are not under the control of the mill personnel and that may also account for differences in the initial performance of the mills as well as the achievable progress.

- The mills do not have the same age: (Mill A ~ 40 years; Mill B ~ 25 years; Mill C ~ 80 years)
- The mills manufacture different products: dissolving pulp for mill A, non coated paper for mill B and coated paper for mill C.
- Their processes, although of the Kraft type, differ on some points: Mill A is equipped with batch digesters, which consume more steam per ton of wood processed than the continuous digesters utilized by mills B and C.
- In mill A, the wood chips undergo a pre-hydrolysis before digestion (a requirement of the manufacturing of dissolving pulp) that requires steam.

On the basis of these process and product differences, it could have been anticipated that mill A would have higher water consumption and therefore a higher potential for water savings. But this is not the case. It can be assumed that energy management has also been an important factor in the differences between the three mills. For example, mill C may not have been keeping up with the efforts of the industry to improve its steam and water efficiency. The potential efficiency improvement of this mill is in the 40% range for both steam and water. Mill A has the best steam utilization efficiency and mill B the best water utilization efficiency in their current configuration. Both of these mills are reasonably well managed, however, both can still make significant progress; consumption of steam or water could be reduced by at least 25%.

Mills A and C, which are still using fossil fuels to fire power boilers, could stop this practice by application of the proposed energy efficiency enhancement program, thus reducing the recovery period of the required investment.

Figure 6.1 gives water savings and steam capacity production liberated as percent of current production and key economic data including payback times for the complete application of the program. The payback time is particularly short for mill C (less than a year) because of its lower initial performance. Table 6.1 gives the same data per adt.

The energy efficiency in the three mills studied has been raised to an efficiency level close to the 75th Canadian percentile for mill A, to the median level for mill B, and to the 25th percentile level for mill C, as it can be seen from tables 2.6 and 6.1.

The economic assessment has taken into account the potential benefit of using the excess steam production capacity to generate additional revenues by the sale of electricity when feasible. Despite the significant investment required, the payback time would remain of the order of two to 3 years for mills A & B. In the case of mill C the excess steam production capacity created by the shutdown of the three power boilers fired with natural gas does not warrant the installation of a cogeneration unit; the significantly reduced expense fully justify the implementation of the proposed energy efficiency enhancements.

The sale of steam has also been considered for mill B, but it is less advantageous than power generation for the assumed market conditions.

An alternative use of part of the excess steam capacity could be to supply the heating and cooling requirements of integrated forest biomass refineries as illustrated by values given in Table 6.2.

Table 6.1: Water and steam savings by pulp unit production rate (adt)

	Mill A		Mill B		Mill C	
	Before	*After*	*Before*	*After*	*Before*	*After*
Water Consumption (m3/adt)	80	49	40	30	120	47
Steam Consumption (GJ/adt)	28.9	21.1	21.9	17.4	22.9	13.7
Water saving (%)	38		24		49	
Steam saving (%)	27		33		43	

Table 6.2: Heating and cooling requirements for typical wood biomass refineries (MW)

Bioproducts	Base requirements		Minimized requirements	
	Heating	*Cooling*	*Heating*	*Cooling*
Ethanol	8.9	21.1	4.7	16.7
Furfural	14.5	25.6	8	19

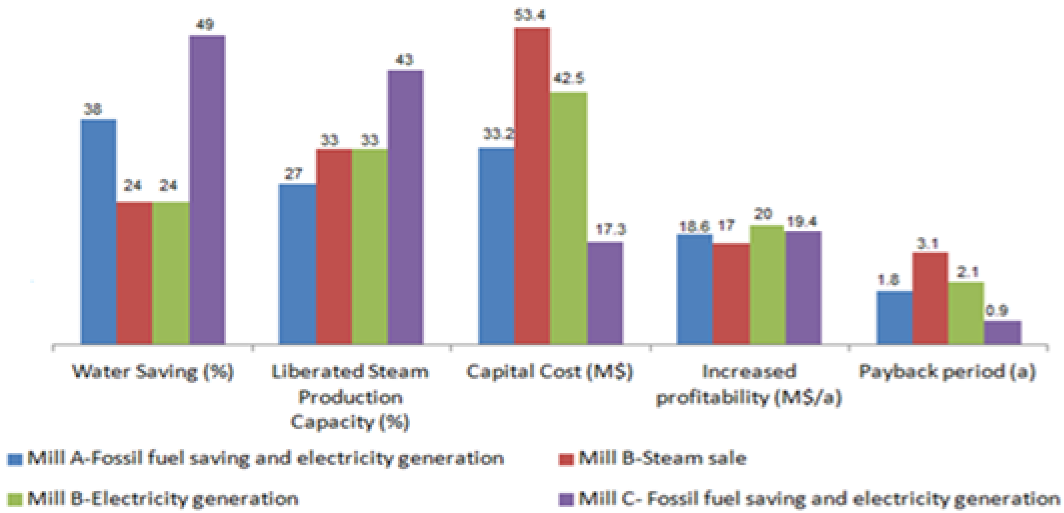


Figure 6.1: Comparative results for the three mills

In conclusion, a new and innovative methodology for the analysis and enhancement of the energy efficiency of P&P processes has been formulated and tested by its application to three operating Canadian Kraft mills. This methodology does not utilize complex computing and optimization techniques. It relies, on the contrary, on basic engineering ways:

- The observations and evaluation of the current performance of key equipment and process sectors;
- A combined steam and water systems analysis;
- The identification of interactions between the various modes of thermal energy production and delivery.

Very importantly, it follows a project oriented approach. Taking into account the fact that pulp and paper making is essentially a water-based process, it utilized the so-called water-pinch analysis method but in a form which incorporates the heat content of water streams. It also focuses of the various ways in which steam is used to reduce thermodynamic inefficiencies. It is intended to be used by process engineers in the P&P industry and in other industries also relying on water-based processes such as the mining, metallurgy and agro-food industries.

The source of data utilized to perform the successive steps of the analysis is a computer embedded process simulation. This simulation represents the long term averaged process steady-state. The development of such simulation is a very tedious and time consuming task. Work has been undertaken to overcome this obstacle. It involves the development of new, more appropriate energy and material performance indicators and the application of data reconciliation techniques.

The methodology has been applied to three different operating Canadian Kraft pulping mills. The differences include time of constructions, process configurations and operation. In the three cases, the potential reductions in steam and water consumptions are in the high range or above results obtained by conventional engineering practice; the return on the investment is high and pay-back time attractive. It is intended that work be pursued to incorporate key process simulations development steps and that a computer aided implementation procedure be offered to the industry.

A prerequisite to the sustainability of the integrated forest biorefinery is a high level of efficiency of the receptor P&P mill in particular in regards to the consumption of steam and water.

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